SHIFTING ERUPTION STYLES DURING THE EMERGENCE OF AKAROA STRATO-SHIELD VOLCANO, BANKS PENINSULA, NEW ZEALAND.

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Abstract

The uniquely eroded harbour of Akaroa volcano provides a rare opportunity to study the dissected core of the basaltic to trachytic strato-shield volcano. With key exposures of both the early phase trachytic to basaltic eruptive deposits and the later phase voluminous basaltic deposits (9.6 – 8.6 Ma) that make up the majority of the emergent volcanic flank.

This thesis aims to illustrate the volcanic processes that dominate the diverse early stages of emergent volcanism. We have built on previous research to produce detailed maps and stratigraphic logs of key extrusive and intrusive sequences. We further identify eruptive packages and their facies to identify eruptive centres, and correlate early stratigraphy.

This study reveals the emergence of local volcanic centres with differing eruptive styles, chemistry and volumes. An explosive phreatomagmatic trachyte tuff ring and dome/flow complex dominated early eruptions. This extensive trachytic centre had multiple phases of activity, displaying both temporal and spatial transitions in style. Temporal facies transitions consisted of changes from a subaqueous to emergent hyaloclastite dome, to an explosive phreatomagmatic trachyte tuff ring to an effusive trachytic dome (Fig 7.1 – Fig 7.7). Whereas spacial transitions consisted of lateral facies variations within the pyroclastic surge and air fall deposits of the tuff ring reflecting 'en route' changes in deposition.

Smaller volcanic centres migrated around the margins of this larger trachytic centre (Fig 7.1 – Fig 7.7). These eruptions variously interacted with seawater forming small tuff and scoria cones. Generally, these smaller eruptions show a progression from low angle phreatomagmatic palagonite rich lapilli tuffs to steeper bedded spatter and bomb dominated deposits. This transition in facies likely represents the emergence of individual volcanoes with later deposits showing less evidence for interaction with seawater. These discrete centres later coalesced through deposition of the more extensive lava flows forming the early volcanic complex of Akaroa Volcano.

Erosional processes dramatically reshaped the volcanic complex. Bays of the present day harbour represent eroded basaltic explosive centres, as pyroclastic units are preferentially eroded by the sea. Whereas more coherent lavas tend to form headlands within the harbour.

In summary, the findings of this research have refined maps, stratigraphy, lithologic descriptions and facies interpretations of Akaroa volcanoes emergent deposits. Thus enabling the development of a geological formation model for the early to emergent stages of Akaroa Volcano. Furthering the understanding of early to emergent, shallow magmatic, volcanologic processes, associated with alkali basaltic and trachytic eruptions at Akaroa Volcano.

1. Introduction

In old volcanic complexes erosional processes reshape the landscape and dramatically alter its' primary volcanic landforms (Hampton 2009). Previously, researchers have shown that the location and identification of primary volcanic landforms, eruptive centres, and vents can be reconstructed by studying the orientation and structures and textures of volcanic deposits (Moore et al.1990; Johnston et al. 1997; Cole et al. 1999; Németh and White 2003; Kereszturi 2010). Németh and White (2003) utilised a facies association approach, where correlated stratigraphic logs are used to describe deposits, interpret depositional setting and classify facies into facies associations. This approach using lithofacies associations, combined with the ratio of preserved pyroclastic versus lava units, and the size of deposits, allow highly eroded vents to be characterised and reconstructed.

Younger volcanic centres of similar size and composition also provide a useful analogy to relate volcano morphology to vent location and the identification of eruptive packages (i.e. distinct phases or periods of eruptive activity clearly identifiable within a sequence of volcanic deposits). At Sao Miguel Volcano, Azores, trachytic packages are characterised by relative proportions of ash, and lapilli to identify variations in water magma interaction (Zanon et al. 2009). These packages are correlated in coastal cliff exposures to constrain vent location, shifting eruption styles and caldera boundaries (Moore et al. 1990).

The two large eroded Miocene composite shield volcanoes (Lyttelton and Akaroa) that form Banks Peninsula, New Zealand (Fig 1.1), have long been interpreted as single volcanic edifices (Weaver and Smith 1989; Shelley 1987, 1992). Recent geomorphological studies on Lyttelton Volcano (Hampton and Cole 2009) highlight a more complex volcanic evolution than previously proposed. Hampton and Cole (2009) identified multiple eruptive vents in contrast to the existing single vent model (Shelley 1992). The study concluded that on Lyttelton Volcano variations in individual eruptive packages relate to the geochemical and physical properties of the magmatic source.

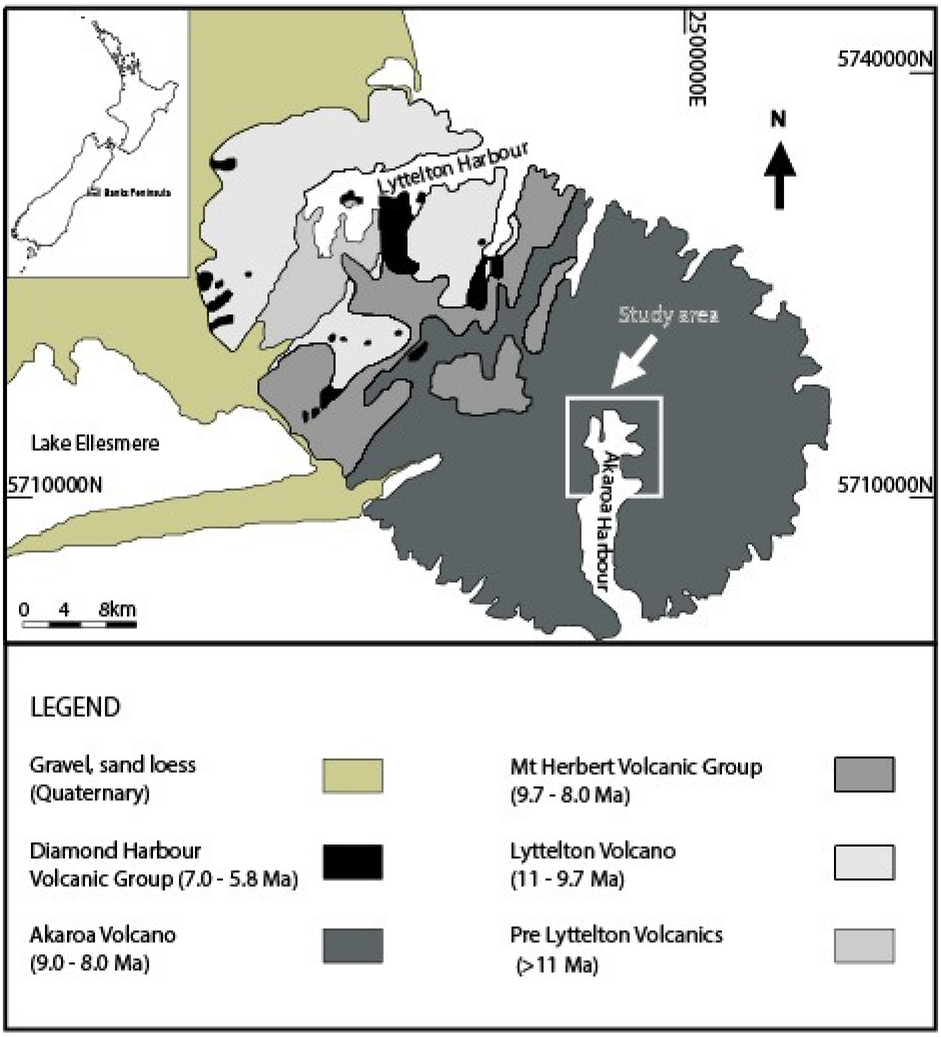


Figure 1.1 Geological map of Banks Peninsula adapted from Hampton and Cole (2009)

Few places in the world allow the study of how large composite shield volcanoes evolve (Martin 2000). In New Zealand, Banks Peninsula provides a rare opportunity to study and understand the construction of large basaltic to trachytic strato-shield volcanoes. Akaroa Harbour is of particular geological significance as it provides excellent exposure of the full volcanic sequence; from the emergent basal sequence through the dissected volcanic flanks of Akaroa Volcano.

Previous studies focused on the overall development of Banks Peninsula, identifying sources and periods of volcanism, developing maps and a stratigraphy (Haast 1878; Speight 1917, 1923, 1940, 1944; Liggett and Gregg 1965; Stipp and McDougall 1968; Price and Taylor 1980; Falloon 1982; Thiele 1983; Sewell 1985, 1988; Sewell et al. 1992). Other studies focused on modelling of the magma source and geochemical evolution (Ligget and Gregg 1965; Price and Taylor 1980; Weaver and Sewell 1986; Barley and Weaver 1988; Dorsey 1988; Sewell et al. 1993; Johnston et al. 1997; Hoke et al. 2000; Timm et al. 2009). The most recent studies provided new $^{40}Ar/^{39}Ar$ dates for Banks Peninsula and use major and trace element data to suggest the chemistry is consistent with melting a peridotite and eclogite source during lithospheric detachment (Timm et al. 2009) indicating a deep seated magma source.

Relatively little detailed research has been conducted on the shallow magmatic and eruptive processes of Akaroa. Dorsey (1988) primarily focussed on large scale unit mapping and lithologic descriptions to support a geochemical study, interpretations of eruptive mechanisms and styles were minimal. Dorsey (1988) defined eruptive phases into early I, II, III and the main phase based on stratigraphy and chemical differences. The main phase of volcanism was distinguished from the early phases by the presence of an unconformity, citing evidence as the change in dip 5 – 10 at the contact and the relative freshness of the overlying flows.

The stratigraphic units of the whole of Akaroa Volcano are defined by seven formations (Sewell 1988) which include mafic and felsic volcanic products from central, flank and parasitic vent eruptions as well as shallow intrusions and minor plutonics.

The latest work on the Akaroa Volcanics was a companion study with primarily a geochemical approach. Hartung's (2011) study focused on the compositional gap or 'daly gap' and proposed stepped fractionation and melt extraction as the preferred model of generation.

This study is focussed on the early stages of development of Akaroa Volcano. As outlined earlier, exposures within Akaroa Harbour provide a sequence through the emergent stages of volcanism, an aspect not exposed elsewhere on Banks Peninsula. In this study, we distinguish primary morphological features from subsequent erosion, and attribute the primary cone characteristics to changes in eruptive style that relate to chemistry, magma ascent, fragmentation, and water interaction. We focus on the physical volcanology of the diverse early stages of volcanism of Akaroa Volcano, with the aims of identifying (1) the depositional settings, and facies associations, (2) spatial distribution of eruptive vents, and (3) the temporal transitions in eruption styles, both within eruption sequences and throughout the evolution of the emergent volcano. The overall aim of this study is to create a model for the emergent early stages of volcanism of Akaroa Volcano.

2. Geology and tectonics

Banks Peninsula is situated mid way along the East Coast of New Zealand's South Island, bordering the Canterbury Plains (Fig. 1.1). The volcanic complex of Banks Peninsula is ~1200 km^2 and is comprised of two overlapping, extinct, strato-shield volcanoes; Lyttelton Volcano (11 – 9.7 Ma) and the larger Akaroa Volcano (9.3 – 8 Ma) and the contemporaneous Mt Herbert Volcanic Group (9.7 – 8.0 Ma) and the later Diamond Harbour Volcanic Group (8.1 – 5.8 Ma) (Sewell et al. 1992). These eruptions formed a strato-shield island ~10 km off the coast that later became connected to the mainland by a combination uplift in the west increasing erosion rates, resulting in east Coast progradation (20, 000 years ago) (Adams 1981) and sea level fall (Dorsey 1988).

Intraplate volcanism at Banks Peninsula occurred during a period of crustal extension. It is proposed that magma was generated from lithospheric detachment causing melting and upwelling of upper asthenosphere and portions of the removed lithosphere (Timm 2009). Timm et al. (2010) proposed a large seismic low velocity anomaly between West Antarctica and Zealandia at a depth of >600 km. This zone may represent a geochemical reservoir that supplied the upper mantle of Zealandia with HIMU plume material during the Cenozoic. The cessation of volcanism in the South Island occurred during the change from strike slip to compressional tectonics (Hoke et al. 2000).

Volcanism at Akaroa Volcano was diverse in style consisting of effusive, explosive and intrusive magmatism. The deposits are encompassed by seven formations (Sewell 1988) which include mafic and felsic lava flows, pyroclastics, domes, dykes and plutonic intrusions. Mafic volcanism dominated the shield-forming stage, which included hawaiian and mildly strombolian eruptions and basaltic to hawaiite lava flows. However, both the early and late phases of volcanism were also accompanied by trachytic volcanism, characterised by both pyroclastic and effusive eruptive styles`.

3. Methodology

3.1 Terminology and classification schemes

Classification schemes used in this thesis include the IUGS classification for igneous rocks and White and Houghton's (2006) classification of primary volcaniclastics and sedimentary deposits (Table 3.1). White and Houghton's classification scheme defines volcaniclastic deposits as "deposits directly related to a volcanic eruption;" and epiclastic deposits as "deposits resulting from the reworking of volcanic material." Volcaniclastic deposits are therefore defined as pyroclastic, autoclastic, hyaloclastic and peperitic (Table 3.2), while epiclastic deposits are classified using sedimentary terminology (Table 3.1). Clasts within both primary volcaniclastic and epiclastic deposits are described using White and Houghton's (2006) component classes (Table 3.3), components are separated into juvenile, lithic and composite.

Grain-size Terms For Primary Volcaniclastic Rocks					
Grain size		**Primary volcanicalstic deposit**		**Sediementary deposits (rock name)**	
phi	**mm**	**Unconsolidated**	**Lithified**	**Unconsolidated**	**Lithified**
>4	<1/16	Extremely fine ash	Extremely fine tuff	Clay	Mudrock, shale
3 – 4	1/16 – 1/8	Very fine ash	Very fine tuff	Very fine sand	Very fine sandstone
2 – 3	1/8 – 1/4	Fine ash	Fine tuff	Fine sand	Fine sandstone
1 – 2	1/4 – 1/2	Medium ash	Medium tuff	Medium sand	Medium sandstone
0 – 1	1/2 – 1	Coarse ash	Coarse tuff	Coarse sand	Coarse sandstone
-1 to 0	1 – 2	Very coarse ash	Very coarse tuff	Coarse sand	Coarse sandstone
-2 to -1	2 – 4	Fine lapilli	Fine lapilli tuff	Granule	Grit, granule conglomerate
-4 to -2	4 – 16	Medium lapilli	Medium lapilli tuff	Pebble	Pebble conglomerate
-6 to -4	16 – 64	Coarse lapilli	Coarse lapilli tuff	Cobble	Cobble conglomerate
< -6	>64	Block/ bomb	Breccia	Boulder	Boulder conglomerate
Note: The ash and lapilli grain-size ranges have been modified from that given by Fisher (1961) and derivative classifications to match and include the subdivisions within the sand and gravel ranges given by Wentworth (1922). "Extremely fine" ash replaced "fine ash" for particles finer than 4 phi (1/16 mm). Lithified sedimentary deposits with angular grains coarser than 2 mm are commonly termed "breccia".					

Table 3.1 Grain size terminology for primary volcaniclastic and sedimentary deposits (White and Houghton 2006)

Varieties of Volcaniclastic rocks	
Process	**Deposit adjective (noun)**
Sedimentation from pyroclastic plumes and currents	Pyroclastic (various)
Deposition of fragments from lava, formed via air cooling	Autoclastic (autobreccia)
Deposition of fragments from lava, formed via water chilling	Hyaloclastic (hyaloclastite)
Mingling of magma with wet sediment, in situ deposition	Peperitic (Peperite)
Note: All should be given grain-size names based on grain size and degree of lithification	

Table 3.2 Varieties of Volcaniclastic rocks (White and Houghton 2006)

Component Classes For Volcaniclastic Deposits		
Component	**Key criteria**	**Components within deposits**
Juvenile	Primary juvenile: derived directly from erupting magma; particle contributes heat to thermal budget of transport and/or fragmentation processes. Recycled juvenile: Juvenile clast recycled during the eruption that formed it; not a significant thermal contributor to depositing plume or current	Dense to inflated fragments of chilled magma (Pumice, Scoria, Dense juvenile); may be recycled. Aggregate of relatively finer- grained clasts (accreationary lapilli, armored lapilli). Crystals derived directly from the erupting magma (e.g., Juvenile feldspar); may be recycled.
Lithic	Clast formed by fragmentation of pre-existing rock or incorporated from unconsolidated sediment. These contribute negligible heat energy to transport, depositional or fragmentation processes.	Fragments derived from wall rock (e.g., sandstone lithic). Fragments of solidfied magma from conduit walls, blocks of lava or dyke rock (e.g., basalt lithic). Block of pyrocastic rock (e.g., tuff block).
Composite	Clast formed by mingling of magma with a clastic host, or incorporation of lithic debris into magma.	Fragments of peperite (composite clasts). Bomb with lithic core (cored bomb).
Note: Though “juvenile” is subdivided to distinguish primary from recycled clasts, it is recognised that this significant behavioural distinction can only rarely be made from ancient deposits. Composite clasts are unique in combining lithic and juvenile material.		

Table 3.3 Component classes (White and Houghton 2006)

3.2 Techniques and Methods

Detailed field investigations (4 months) were conducted along the inner shoreline of Akaroa Harbour from the head of the harbour at Onawe Peninsula to Childrens Bay in the east and Anchorage Bay in the west (Fig 3.1 see appendix). Fieldwork was conducted from shore platforms and sea kayaks.

Geological Mapping

Geological mapping was conducted around inner shorelines of Akaroa Harbour to identify eruptive centres. This included defining and describing lithologic units using the White and Houghton classification schemes (2006) and mapping their extent using Google Earth images and Topographic maps as base maps. Key sections were located using hand held Garmin GPS units, with a horizontal accuracy of ~5m. Strike and dip measurements of lava flows and pyroclastics were taken to identify flow directions and ballistic trajectories.

Stratigraphic Logging

Stratigraphic logs presented in this study focus on areas where continuous sequences could be related to the development of the emergent Akaroa Volcano. Stratigraphic logs highlight textural variations within and between eruptive packages. Units were classified based on their grain size (e.g. tuff, lapilli tuff, tuff breccias), sorting, clast shape, composition (e.g. Juvenile or lithic), texture (e.g clast vs matrix supported) and bedding (e.g stratified, massive, dune bedded). Clast counts were conducted at key outcrops to assess outcrop scale proportions of lithics and juvenile clasts. This classification of units enabled the recognition of distinct layers or beds, thereby allowing eruptive packages to be defined.

Outcrop descriptions and thin section analysis

Outcrop scale descriptions were complimented by petrographic and textural analysis of thin sections. Overr 100 rock samples were collected from the volcanic and plutonic deposits of Akaroa Harbour. These were grouped according to mineral assemblage and texture and from these, 60 were selected for thin sections. The most texturally interesting parts of the rock were selected for thin sections, ground down to a 0.3mm thickness and mounted onto a glass slide with resin. In addition to these 60 new sections, 11 pre-existing sections from Dorsey's study (1988) were also described in detail. Thin sections description of pyroclastic samples included grain size, angularity, sorting, vesicularity, and the proportion of juvenile to lithics and structures at a mm to µm scale. Thin section descriptions of lavas focused on grain size, crystal shape, mineralogy, vesicularity and structures. This thesis presents 20 representative descriptions in the following chapters that are characteristic of the textural and mineralogical variation around the harbour.

Geochemical analysis

X-ray fluorescence (XRF) analyses were conducted for the purpose of chemically distinguishing rock types and to correlate units. Analyses were conducted at the University of Canterbury, using a Philips PW 2400 Sequential Wavelength Dispersive X-ray Fluorescence Spectrometer calibrated to international standards. We collected 51 fresh hand samples for geochemical analysis. The least weathered sections of the samples were

selected, and these were cut, crushed, pulverised and milled to insure a small uniform particle size to avoid particle size effect problems.

The samples were pre-treated using the fused disc treatment for major elements and powder pellet treatment for trace elements. Preparation of glass fusion beads involved fusing together approximately 1.3g of rock powder with 6.98g of flux ($Li_2B_4O_7$, Li_2O and La_2O_3 mixture) and a few grains of oxidant (NH_4NO_3). Fusion occurred at 1030 ˚C for at least 15 minutes in Pt/Au crucibles. Following fusion loss on ignition (LOI) was calculated. The glass beads were created by cooling the molten material in Pt/Au moulds. Major element chemistry is determined on fusion beads using a rhodium tube set at 50kV/55mA

Trace element analyses used the powder pellet treatment, 8g of rock powder was bound with an equal amount of polyvinyl alcohol solution. The mixture was pressed in a hardened steel die at 3000 psi for 10 sections into 32mm diameter pellets. The trace chemistry is determined on pressed powder pellets using a rhodium tube set at 60kV/46mA.

30 new bulk-rock analyses (reduced data) are presented in the following chapters. The data is presented in TAS diagrams plotted using IGPET Software. The selected samples represent characteristic rocks types of the area. The complete data set is provided in the supplementary material of the geochemical companion study conducted by Hartung (2011).

Facies interpretation and fence diagrams

Stratigraphic logs, lithologic descriptions and geochemistry allowed eruptive packages to be identified, while the spatial distribution of these packages allowed the recognition of distinct facies. Facies that frequently occurred together in the same stratigraphic level were grouped as lithofacies associations. Fence diagrams of lithofacies were drawn up to graphically display the relationship of units across the harbour. These plots aided in the identification of eruptive vents and the reconstruction of eruptive centres.

4. Stratigraphy

The deposits located around the central harbour of Akaroa represent the emergent and early subaerial phases of volcanic activity at Akaroa Volcano. The stratigraphic descriptions by Dorsey (1988), Sewell (1988) and our own field observations indicate transitions in volcanic style and composition. Clear shifts from dominantly basaltic to trachytic volcanism and back to basaltic volcanism prior to Main Phase activity are apparent.

In the following sections we collate previous research (Thiele 1983; Sewell 1985; Shelley 1987; Barley et al. 1988; Sewell et al. 1988; Weaver and Smith 1989; Shelley 1992; Sewell et al. 1992) with our current work to propose a revised detailed stratigraphy for emergent and early phase volcanism at Akaroa Volcano. Note that the most recent dates (Timm et al. 2009) have not been used due to inconsistencies with the recognised stratigraphy of Banks Peninsula.

Akaroa Volcanic Group (9.1 – 8 Ma)

Akaroa volcano erupted from 9.3 – 8 Ma producing a 1200 Km^3 strato-shield, with an estimated height of 1800m above sea level (Weaver and Smith 1989). The basement rocks of Akaroa Volcano are not exposed. However clasts of Torlesse sandstone are incorporated in a basaltic tuff exposed on Onawe Peninsula, suggesting that Akaroa Volcano is constructed over Torlesse basement rocks. The deposits of Akaroa volcano overlap temporally with the Mt Herbert Volcanic Group (Fig 4.1) that are exposed between Lyttelton and Akaroa Volcanoes. The main formations of Akaroa include (1) mafic and intermediate deposits of the Harbour Formation (*hf)* (Hartung 2011), (2) trachytic pyroclastics of the Lushington Breccia (*al*), (3) exogenous trachyte dome of the Tikao Trachyte (*at*), and (4) mafic lava flows, cinder cones and pyroclastics of the both older early French Hill Formation (*af*) and the shield building later French Hill Formation (9.0 – 8.3 Ma) (Fig 4.1). Significantly, the French Hill Formation does not distinguish between the Early Phase and Main

Phase deposits of the shield-building stage that are marked by an unconformity. Therefore, we term the older phase deposits the Early French Hill Formation and the shield-building deposits the Later French Hill Formation. (5) mafic lava flows and pyroclastics of the later flank eruptives of the Mt Sinclair Formation (*am*) (8.6 – 8.3 Ma), (6) the Hawaiite flows of the Te Oka Formation (*ae*) (8.3 – 8.1 Ma) (Fig 4.1). These formations are comprised of alkali lavas, pyroclastics and shallow intrusives. Extrusive deposits are dominated by hawaiite compositions and shallow intrusives by benmoreite and trachyte compositions (Dorsey 1988). Intrusive rocks exposed on Onawe Peninsula consist of the Duvauchelle Gabbro (ad) (8.92 Ma) and the Onawe Syenite (ao); these deposits intrude the early volcanics and are thought to be late stage (Fig 4.1).

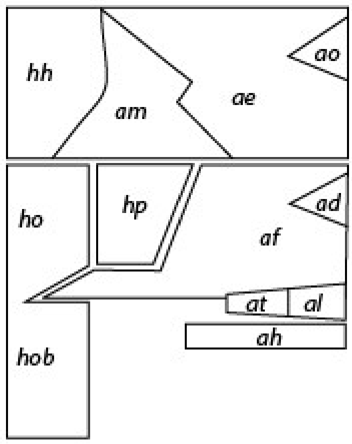


Fig 4.1 Overview stratgraphic log (adapted from Sewell et al. 1992) of Akaroa Volcanic Group and Synactive Mt Herbert Volcanic group , Banks Peninsula, depicting the timing relationships and distribution of the different formations Herbert Peak Hawaiite (*hh*) , Mt Sinclair Formation (*am*), Te Oka Formation (*ae*), Onawe Syenite (ao), Orton Bradley Formation (*ho*), Port Levy Formation (*hp*), French Hill Formation (*af*), Duvachelle Gabbro (*ad*), Lushington Breccia (*al*), Tikao Trachyte (*at*), Harbour Formation (*ah*).

Harbour Formation *hf*

The Harbour Formation (*ah*) (Hartung 2011) represents the earliest volcanic products of Akaroa volcano (Fig 4.1). It consists of (> 2 m) basal basaltic lava flows dipping beneath the Lushington Breccia Formation (*al*) exposed on Onawe Peninsula (Fig 3.4). The contact between the Harbour Formation and Lushington Breccia Formation is obscured by a sill (Fig 4.2) and therefore the nature of the contact is unknown.

Lushington Breccia Formation *al*

The Lushington Breccia Formation (*al*) (Sewell 1992) consists of trachytic tuff breccias, lapilli tuffs and tuffs. At the type locality in Lushington Bay (Fig 3.4 see appendix), more than ~13.6 m of unit is exposed. However outcrops are extensive around the inner harbour, with deposits present in Takamatua Bay (>8m), the southern end of Onawe Peninsula (>7.2 m), between Barrys Bay and French Farm Bay (>6.2 m) and on the Southern shore of French Farm Bay (>3.4 m) (Fig 3.4 see appendix). The deposits consist of weakly bedded, blue grey, poorly to moderately sorted, clast supported, angular to sub-rounded, polylithic, trachyte tuff breccia to trachyte tuff. The top contact is observed at French Farm Bay and Lushington Bay where it is overlain by the French Hill Formation (Fig 4.3). This unit has not been dated; however stratigraphic relationships, chemistry and dyke relationships suggest it occurs contemporaneously with the French Hill Formation and prior to the Tikao Trachyte (Fig 4.1).

Tikao Trachyte Formation *at*

The Tikao Trachyte Formation (*at*) (Sewell 1992) is a trachytic exogenous dome located on the western side of Akaroa Harbour, between Tikao Bay and Petit Carenage Bay (Fig 3.4 see appendix). The dome consists of massive fine grained aphyric weakly plagioclase–phyric trachyte with glomerophyric microsyenite exposed on the north east coast. The base of Tikao trachyte is not exposed, however the unit is overlain by a volcanic breccia and conglomerate at Tikao Bay. Suggesting a similar age to the early French Hill Formation (Fig 4.1).

French Hill Formation *af* (9.0 – 8.3 Ma)

The French Hill Formation (*af*) is the dominant formation of Akaroa Volcano, both spatially and temporally (Fig 4.1). It encompasses both early phase deposits and the main shield building stage. An erosional unconformity is present within the French Hill Formation indicating a period of dormancy. This break in volcanism is thought to represent the change between the early and main phases of activity at Akaroa (Dorsey 1988). To differentiate these deposits the older inner shoreline deposits will be referred to as the early French Hill Formation and the main shield-building deposits as the later French Hill Formation. The deposits of the both the early and late French Hill Formation's are dominated by fine grained clinopyroxene – olivine plagioclase phyric and aphyric hawaiite lava flows. However, porphyritic basalt, mugearite, benmorite and trachyte flows and basaltic tuff cones also occur. Flows dip between 5 to 10 degrees from the central crater region and are intercalated with lithic rich tuffs and agglomerates. Numerous dykes cut the deposits, dykes consist of trachyte basalt and phonolite compositions.

Mt Sinclair Formation *am* (8.6 – 8.3 Ma)

The Mt Sinclair Formation (*am*) (Sewell 1992) unconformably overlies the French Hill, Port Levy and Orton Bradley Formations (Fig 4.1). Erupted from a centre near Mt Sinclair this formation consists of 10 – 15 m thick basaltic lavas and pyroclastic material. The lava flows are plagioclase-pyroxene-olivine phyric and aphyric hawaiite in composition and dip between 2 – 5 degrees. This unit is undated; however it is stratigraphically between the Orton Bradley and Herbert Peak Hawaiite and the Te Oka Formation in the south west (Fig 4.1) indicating an age between 8.6 – 8.3 Ma.

Te Oka Formation *ae* (8.3 – 8.1 Ma)

The Te Oka Formation (*ae*) (Sewell 1992) unconformably overlies the French Hill Formation on the Western and Eastern flanks of Akaroa Volcano and Mt Sinclair on the North-western flanks (Fig 4.1). Based on the distribution of lava flows around the outer flanks of Akaroa, a central crater vent during the late phase of activity is proposed (Sewell 1992). Lavas are typically 2-5 m thick and consist of aphyric hawaiite and minor plagioclase phyric hawaiite.

Duvauchelle Gabbro *ad* (8.92 Ma)

Exposed on southern Onawe Peninsula (Fig 3.4 see appendix) the Duvauchelle Gabbro (ad) is a massive biotite-olivine gabbro. The gabbro lies between the Onawe Syenite and the earliest French Hill Formation (Fig 4.1). Although the contact between the gabbro and syenite is obscured by a trachytic dyke on the Western Coast of Onawe Peninsula (Fig 3.4 see appendix), a 1-2 meter area of gabbro on eastern Onawe contains massive pockets of felsic material (Fig 4.4). Schlieren are monzodiorite to monzonite in composition and lensoid in form (Sewell 1992). Dating of the gabbro has found it be contemporaneous with the earliest French Hill Formation (Fig 4.1) (Stipp and McDougall 1968).

Onawe Syenite *ao*

Onawe Syenite (ao) is a massive syenite intrusion exposed on the southern end on Onawe Peninsula (Fig 3.4 see appendix) which outcrops adjacent to the Duvauchelle Gabbro. The unit consists of a creamy yellow, massive, medium grained, spheroidally weathered syenite containing drusy cavities infilled with quartz. Dating of alkali feldspars within the syenite rendered an age of 11.8 Ma; however this is date is unreliable due to gaseous activity accompanying crystallisation, emplacement and subsequent alteration. The relative age of the syenite is unknown; however it is thought to be late stage as relatively few radial dykes are emplaced in this unit. (Fig 4.1).

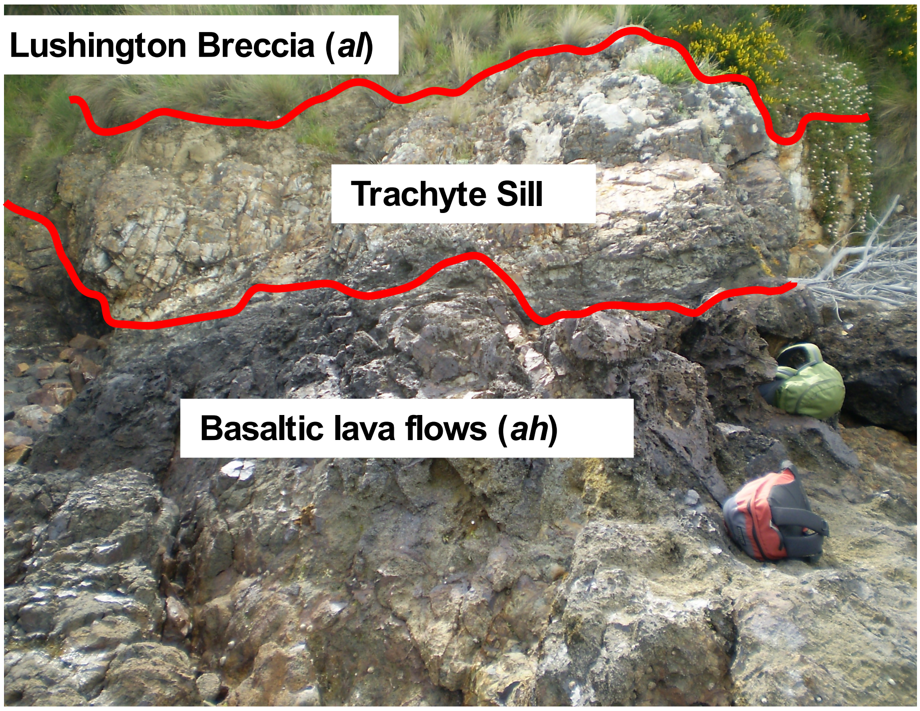


Fig. 4.2 Contact between the Harbour Formation (*ah*) and the Lushington Breccia Formation (*al*) marked by a sill on Onawe Peninsula.

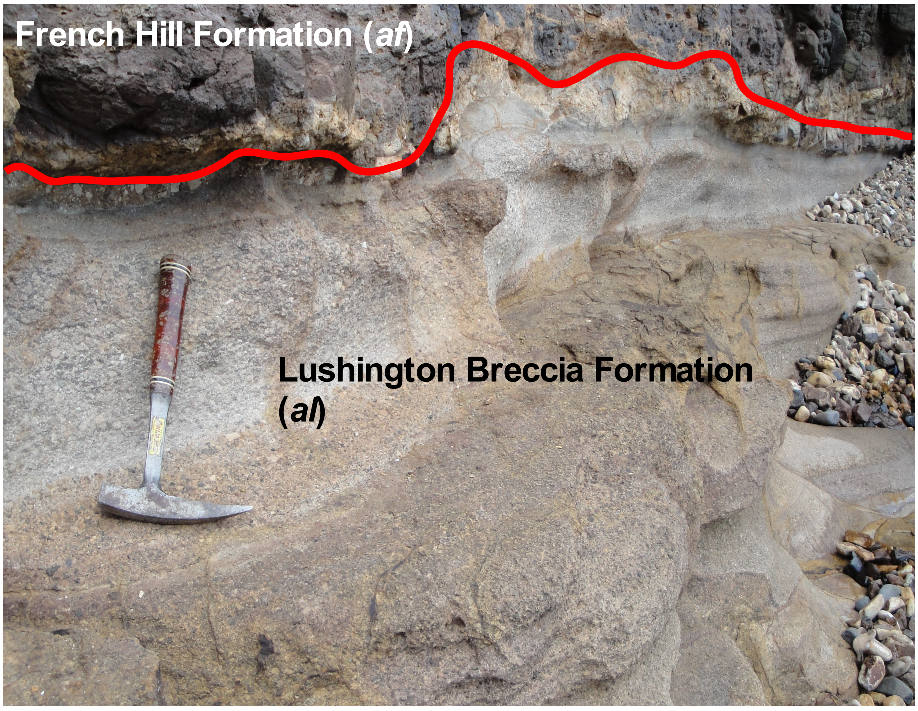


Fig. 4.3 Contact between the Lushington Breccia Formation (*al*) and the French Hill Formation (*af*) at Lushington Bay

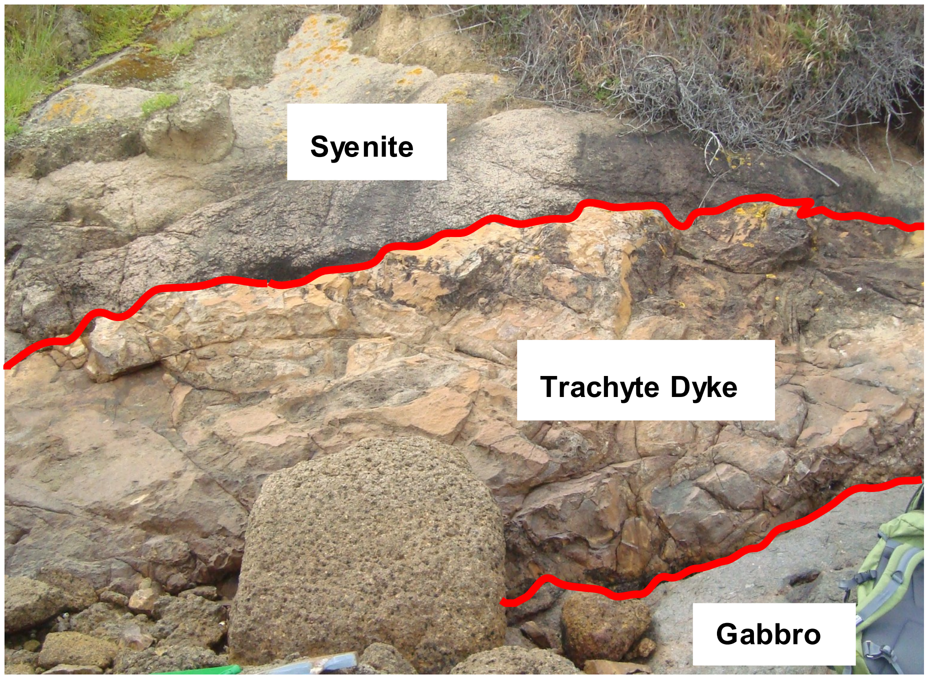


Fig. 4.4 Contact between the Duvauchelle Gabbro (*ad*) and the Onawe Syenite (*ao) marked by a* trachytic dyke on the Western shore of Onawe Peninsula's Southern end.

5. Results

5.1 “Compositional Range”

Rocks from the early emergent phases of Akaroa Volcano display a diverse range in chemistry, from less evolved mafic compositions to more evolved trachytic compositions. Whole rock major element analyses plotted on the TAS classification show that volcanic and plutonic products are mildly alkaline in nature (‘sodic’ series, $Na_2O/K_2O > 2$) (Fig 5.1 see appendix). Deposits range in composition throughout the evolution of the volcano from picritic basalt - alkali basalt – hawaiite – mugearite - benmoreite to trachyte and from gabbro to syenite (Fig 5.1 see appendix). There is a notable deficiency of intermediate rock compositions between 50 to 60 wt.% SiO_2 defines the ‘Daly Gap’ of the early phase of Akaroa Volcano. This 'Daly gap' is a consequence of stepped fractionation and melt extraction (Hartung 2011).

5.2 Geological Map

Geological mapping was conducted around the inner shore platforms of Akaroa Harbour. We present a simplified geological map (Fig 5.2 see appendix) of the central section of Akaroa Volcano. This map is a compilation of new field observations, measurementsss and interpretation (this thesis and Hartung 2011) and interpretations and previous geological maps created by Dorsey (1988) and Sewell (1988). The map depicts the range, extent and locations of trachytic rock types and proposed eruptive centre of the Lushington Bay Formation (al) and Tikao Trachytic Formation (at). It also illustrates the location and extent of effusive and pyroclastic deposits of the Harbour Formation (ah), French Hill Formations (af) and the location of the only plutonic deposits exposed on Akaroa Volcanoes.

5.3 Trachytic units

Trachytic deposits occur early in the sequence of Akaroa Volcano following the initial basaltic Harbour Formation (*ah*), the deposits consist of the Lushington Breccia (*al*) and Tikao Trachyte formations (*at*) (Fig 4.1). The Lushington Breccia Formation (*al*) consists of trachytic pyroclastic sequences ranging from tuff breccias to tuffs. Sequences are exposed between Lushington Bay – Takamatua Bay (> 13.6 m total thickness)(Fig 5.23), French Farm Bay - Petit Carenage Bay (> 3.4 m)(Fig 5.26 see appendix), the road cut between French Farm Bay and Barry's Bay (> 6.2 m)(Fig 5.25) and on Onawe Peninsula (> 7.2 m)(Fig 5.20 see appendix) (Fig 5.2 see appendix). Although a coherent sequence is not found at Tikao Bay, isolated pockets of the Lushington Breccia Formation are found both beneath the dome and within dykes that intrude the Tikao Dome (Fig 5.2 see appendix) (Fig 5.3). The other trachytic formation of the early phase of Akaroa Volcano is the Tikao Trachyte Formation (*at)* which consists of a dome located on the western side of Akaroa Harbour, between Tikao Bay and Petit Carenage Bay (Fig 5.2 see appendix).

Lushington Breccia Formation (*al*)

Trachytic Tuff Breccia

Field description

The trachytic tuff breccia is the basal trachytic unit within the trachytic sequence. The deposit is at its maximum thickness between Lushington and Takamatua Bays (>12.5 m)(Fig 5.23), but also outcrops at Onawe Peninsula (~1.1 m) (Fig 5.19), between Petit Carenage and French Farm Bays (~2.2 m) (Fig 5.26 see appendix) and on a road cut between French Farm and Barry's Bay (~2.2 m) (Fig 5.25) (See Fig 5.2 see appendix for outcrop localities). The deposits consist of monomictic massive, matrix to clast supported, poor to moderately sorted, blue to cream tuff breccia (Fig 5.4). Clasts are angular to sub-rounded, up to 50 cm in size (Fig 5.4) and often display jigsaw fit textures (Fig 5.5). Clasts are composed of dense trachyte fragments as well as occasional pumiceous and flow banded clasts (Fig 5.5) (Fig 5.14a).

Thin section description

The matrix of the trachytic tuff breccias consists of a poorly to moderately sorted, fine to course lapilli tuff with clast sizes ranging from 1/4 mm to 4 cm (Fig 5.14a) (Table 5.1). Clasts consist of sub-rounded to angular recrystallised dense (~55%), glassy perlitic (~20%), pumiceous (~5%), flow banded (~5%) and spherulitic (~5%) trachytes with minor interstitial blocky ash size altered shards (~10%) (Fig 5.14a) (Fig 5.14b) (Table 5.1). Some dense clasts contain rare phenocrysts of alkali feldspar. Clasts are highly altered with quench textures and textures that resemble perlites (Fig 5.14b). Glass within the larger clasts has recrystalised to cristobalite and alkali feldspar sometimes forming spherulites and the alkali feldspar has altered to sericite (Fig 5.14b) (Table 5.1). Rare tube vesicle textures are preserved in some pumice.

Trachytic lapilli tuff

Field description

Trachytic lapilli tuff occurs as a thin (~70 cm) veneer that overlies the trachytic tuff breccia between Lushington and Takamatua Bays (Fig 5.23)(Fig 5.2 see appendix). However, thicker deposits occur at other localities, Onawe Peninsula (~3.3 m) (Fig 5.19), French Farm Bay - Petit Carenage Bay (~ 1 m) (Fig 5.26 see appendix) and the road cut between French Farm Bay and Barry’s Bay (~1.6 m)(Fig 5.25)(Fig 5.2 see appendix). The Trachyte lapilli tuff consists of a blue to cream, massive to weakly bedded, matrix to clast supported, moderate to well sorted, normal graded, lapilli tuff (Fig 5.6a) (Fig 5.6b) (Fig 5.6c). Coarser layers are typically 5cm thick and show well developed normal grading (Fig 5.6c). Clasts are sub-angular to sub-rounded, typically up to 5 cm in size and are composed of dense trachyte fragments as well as occasional pumiceous and flow banded clasts (Fig 5.6) (Fig 5.15). Rare basaltic bombs occur in this unit on Onawe Peninsula (Fig 5.6b).

Thin section descriptions

The trachyte lapilli tuff is a fine to medium lapilli tuff with grain sizes ranging from 1/4 mm – 1 cm (Fig 5.15a)(Fig 5.15b) (Table 5.1). The deposit is composed of 100% juvenile clasts and matrix. Clasts consist of sub-rounded to angular dense trachyte (~ 40%), perlitic clasts (~ 10%), pumiceous trachyte (~ 5%), flow banded trachyte (~ 10%) and the matrix consists of altered blocky to ragged ash sized shards (~ 35%) (Fig 5.15a) (Fig 5.15b) (Table 5.1). Clasts are highly altered with quench textures that often resemble perlites (Fig 5.15b). Glass within the clasts has commonly recrystallised to cristobalite and alkali feldspar has recrystallised to sericite (Fig 5.15b) (Table 5.1). Alkali feldspar has formed Spherulites in many clasts and some clasts contain rare phenocrysts of altered alkali feldspar and chloritised amphibole (Fig 5.15b)(Table 5.1).

Trachytic tuff

Field description

Trachytic tuff occurs on Onawe Peninsula (Fig 5.2 see appendix) as a 1.6 m thick deposit that overlies the trachytic lapiili tuff (Fig 5.19). A thin veneer (~70cm) also occurs between Barry's and French Farm Bay (Fig 5.2 see appendix) (Fig 5.25). The deposit consists of a blue to cream, massive to laminated, moderately to well sorted, normal graded (5 cm scale) tuff (Fig 5.7)(Fig 5.16a). Bedding is planar with some undulation (Fig 5.7) and courser layers display pinch and swell structures (Fig 5.8)(Fig 5.16a). Accretionary lapilli (1-5mm) occur in ash horizons (Fig 5.8). The composition is almost entirely trachytic although rare basaltic bombs are present.

Thin section descriptions

The Trachytic tuff is a fine to coarse grained tuff with accretionary lapilli, grain sizes ranging from 1/8 to 1 mm (Fig 5.16a) (Table 5.1). The deposit is composed of 100% juvenile ash sized clasts, which consist of dominantly altered blocky to ragged ash sized shards (80%), some glass shards (~15%), pores (~5%) and crystals (tr) (Fig 5.16b) (Table 5.1). Samples are extremely weathered although some chloritised amphiboles are identifiable (Table 5.1). Normal grading and layering is apparent some coarse layers have ripple like structures (Fig 5.16a).

Tikao Dome Formation (*at*)

Trachytic Dome

Field description

Tikao Dome is exposed between Tikao Bay and Petit Carenage Bay (Fig 5.2 see appendix). It is composed of massive pale green to dark green to red, fine grained, mainly aphyric (< 7 % crystals in places) trachyte (Fig 5.9). Within the dome the trachyte grades into a grey-white to purple-brown microsyenite that includes aggregates of coarser grained syenite (Fig 5.10). Rare dykes cut the dome, one of which contains clasts of the trachytic tuff breccia (Fig 5.3).

Thin section description

The trachyte dome is aphanitic to porphyritic. Phenocrysts are low in abundance < 10%, they are typically between 2- 3mm in size and consist of euhedral feldspar (~7%) and a lesser proportion of euherdral to subhedral clinopyroxene (~2%) (Fig 5.17a and Fig 5.17b) (Table 5.2). The groundmass has an average grain size of < 0.2mm and consists of flow aligned feldspar laths (~70%) with lesser amounts of clinopyroxene (~14%), Fe-Ti oxides (~9%) and trace amounts of zircon (Fig 5.17a and Fig 5.17b) (Table 5.2).

Trachytic Dykes and sills

Field descriptions

Trachyte dykes (0.1m to > 6m width) are a prominent feature of the inner shoreline of Akaroa Harbour, with the largest dykes exposed on Onawe Peninsula (> 6m thick). The dykes intrude the inner harbour deposits of the Harbour Formation (*ah*), Lushington Breccia Formation (*al*), Early French Hill Formation (*af*) and the Tikao Trachyte Formation (*at*). However few trachytic dykes cut the Onawe syenite exposed on Onawe Peninsula. Three distinct dyke types occur referred to as a) b) and c): Type a) dykes are the largest and consist of cream to tan, aphyric trachyte dykes that typically range from 0.5m to 6m in width (Fig 5.11). Type b) dykes typically range from 0.5 m to 3 m in size, they are green porphyritic dykes with euhedral phenocrysts < 15 mm (Fig 5.12). The third type, dyke c) are small 0.1 to 1 m green aphyric dykes (Fig 5.13). Cross cutting relationships indicate the aphyric cream dykes are the oldest followed by the porphyritic green dykes and the youngest dykes are the small aphyric green dykes. Some dykes incorporate the surrounding lithologies and accumulate clasts from deposits bellow surface exposures.

Thin section description

Trachytic dykes range from aphanitic to porphyritic. Feldspar-phyric dykes have phenocryst abundances < 30%, crystals are euhedral and are typically ~ 3mm in size, however crystals reach 15mm in length (Fig 5.19) (Table 5.2). Glomerophyric plagioclase and small amounts of biotite occur in some dykes (Fig 5.19) (Table 5.2). Others contain green clinopyroxene phenocrysts, magnetite and/ or amphibole and trace amounts of fayalite (Fig 5.19) (Table 5.2). The groundmass has an average grain size of < 0.2 mm and consists of feldspar laths and minor amounts of iron oxides (< 2%) and trace amounts of clinopyroxene, amphibole and biotite in some samples (Fig 5.18) (Table 5.2).

Formation	Sample No.	Rock Type	Grain size (Average)	Grain size (max)	Sorting	Clast or matrix supported	Angularity	clast shapes	Composition	Other structures
al	3280	***Trachyte breccia***	1 -2 mm	4 cm	moderate	Clast	Sub-rounded to angular	blocky jigsaw like fit	Recrystallised dense clasts 55%, glassy perlitic clasts 20%, pumiceous clasts 5%, Spherolitic clasts 5%, flow banded clasts 5% blocky ash matrix 10%	Spherulites developed in clasts as well as perlite textures. Altered quench textures around clast margins. Clasts are heavly altered to sericite and cristobalite. Rare Fs phenocrysts occur in clasts
al	OPE-AT-02 Ts 2	***Trachytic lapilli tuff***	1/4 - 5 mm	1 cm	moderate	Clast	Sub-rounded to angular	blocky shards	Recrystalised dense clasts 40%, glassy perlitic clasts 10%, pumacious clasts5%, crystals tr, ash 35%	Normal grading apparent. Recrystallisation of clast to sericite and less extensive cristobolite. Perlite textures and spherulites developing in clasts and recrystaliisation of quench margins. Rare altered Fs.
al	EH-O-03 Ts 5	***Normal graded fine to medium trachytic tuff***	Fl 1/8 - 1/4 mm Cl 1/4 - 1/2 mm	2 mm	moderate - Well	matrix	Angular - rounded	blocky shards	Ash 80%, Glass 15%, pores 5 %, crystals tr	Normal grading with courser layers have ripple like appearance.

Table 5.1 Representitive thin section descriptions and modal clast counts of trachytic pyroclastic units

Abbreviations: Ts thin section, Fl fine layer, Cl coarse layer, tr trace amount, Fs feldspar

Formation	Thin section number	Rock Type	Texture	Grain size (Average)	Grain size (max)	Crystal shape	Pcrysts	GM	Other structures
af	OPE-NK-02	***Trachyte (Sill)***	Porphyritic	< 0.2 mm	1- 5mm	Euh - Sub	FS 28% Bt 4%	FS 47%, BT 13%, Fe-Ti Oxides 8%, Am tr, Qtz tr, Zr tr	
at	3252	***Trachyte (Dome)***	Aphanitic & trachytic	< 0.2 mm	2- 3 mm	Euh - Sub	FS 2% CPX 1%	FS 77%, CPX 15%, Fe-Ti Oxides 5%, Zr tr	Flow allignment of feldspar laths
af	OPE-JG-03	***Trachyte (Dyke)***	Aphanitic & trachytic	< 0.1 mm	3 mm	Euh	Kfs tr	Kfs 100%	Flow allignment of feldspar laths
af	3253	***Trachyte (Dyke)***	Porphhyritic	< 0.1 mm	6 mm	Euh - Sub	Kfs 2% Am tr Bt tr	Kfs 90%, CPX 4%, Fe -Ti Oxides 4%	

Table 5.2 Representitive thin section descriptions and modal mineral counts of effusive and intrusive trachytic units
Abbreviations: Euh euhedral, Sub subhedral, Fs feldspar, Bt biotite, CPX clinopyroxene, Kfs alkali feldspar, Am amphibole, tr trace amounts, Qtz quartz, Zr zircon

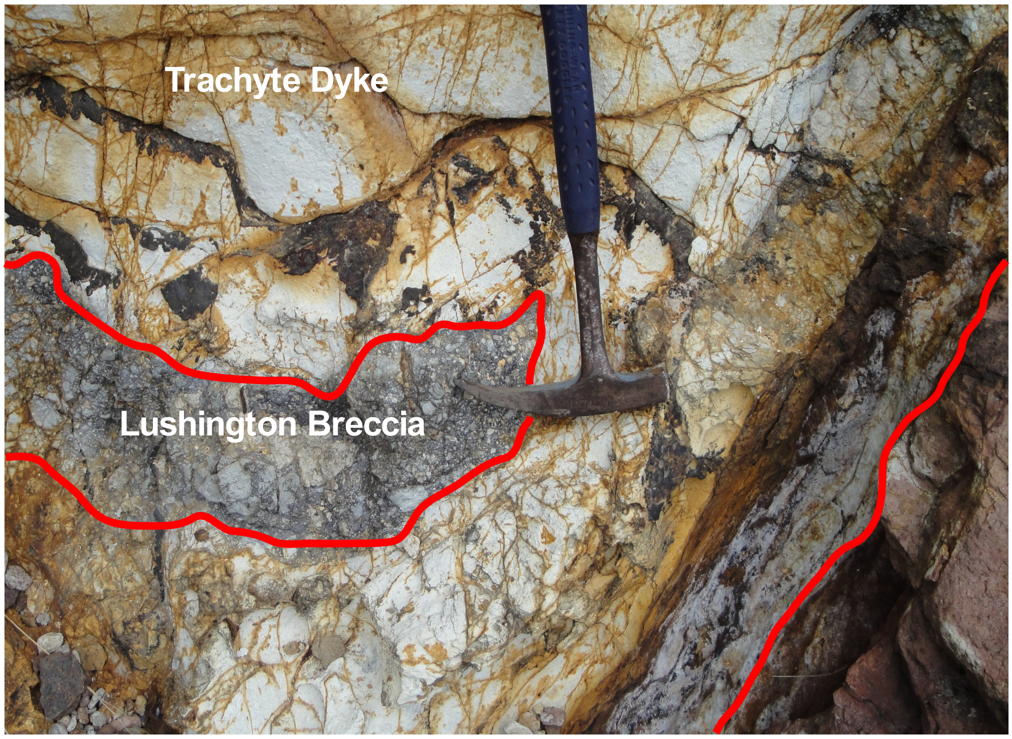


Fig 5.3 Lushington Breccia (*al*) incorporated in trachytic dyke that cuts the Tikao Trachyte Dome (*at*)

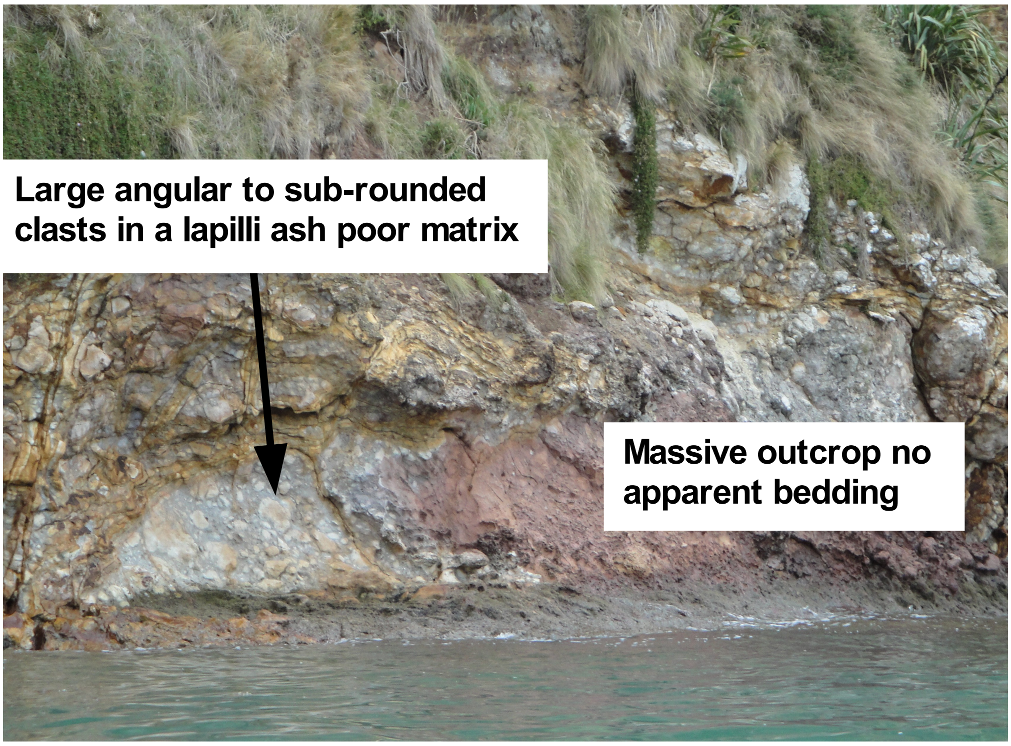


Fig 5.4 Outcrop of the trachytic tuff breccia (*al*) exposed between Lushington and Takamatua Bays showing massive and clast dominated nature of the deposit.

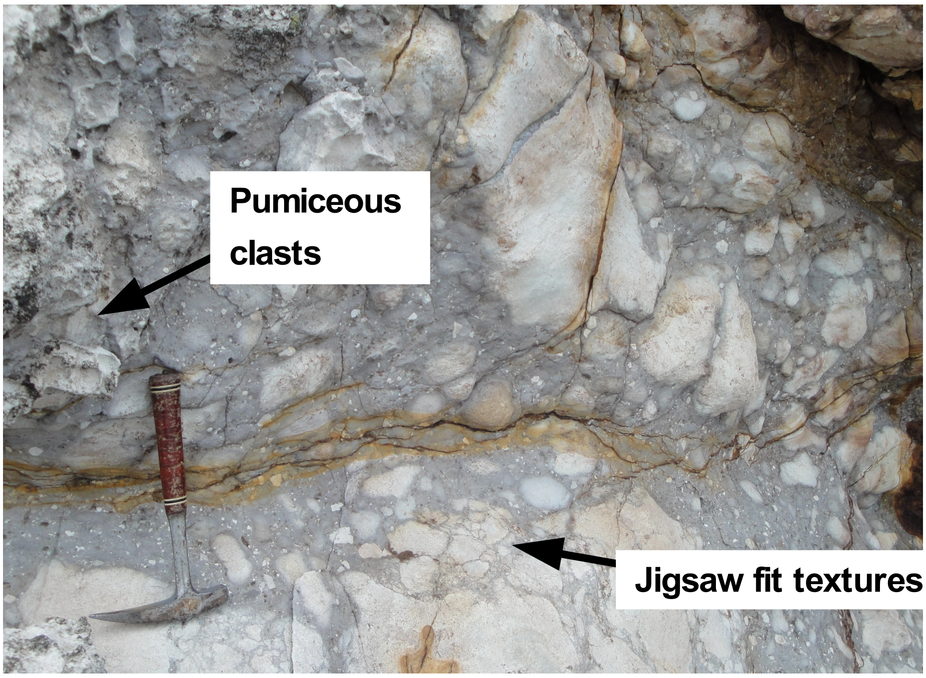


Fig 5.5 Close up outcrop photo of the Lushington Breccia (*al*) showing the range of clast shapes, sizes and textures

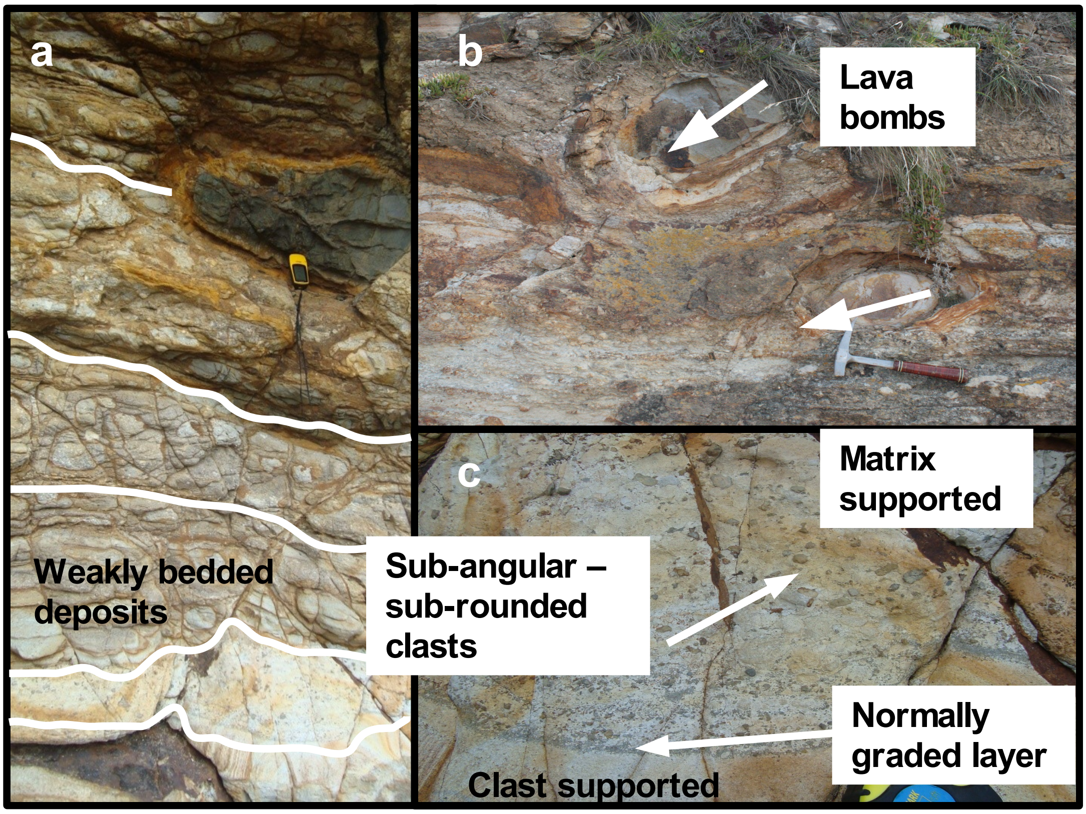


Fig 5.6 Outcrop photo of the Lushington lapilli tuff (*al*) on Onawe Peninsula, showing the range of clast shapes, sizes and textures. a) Shows the weakly bedded nature of the deposit b) shows rare lava bombs in weakly bedded trachyte lapilli tuff c) shows the variation in the nature of beds

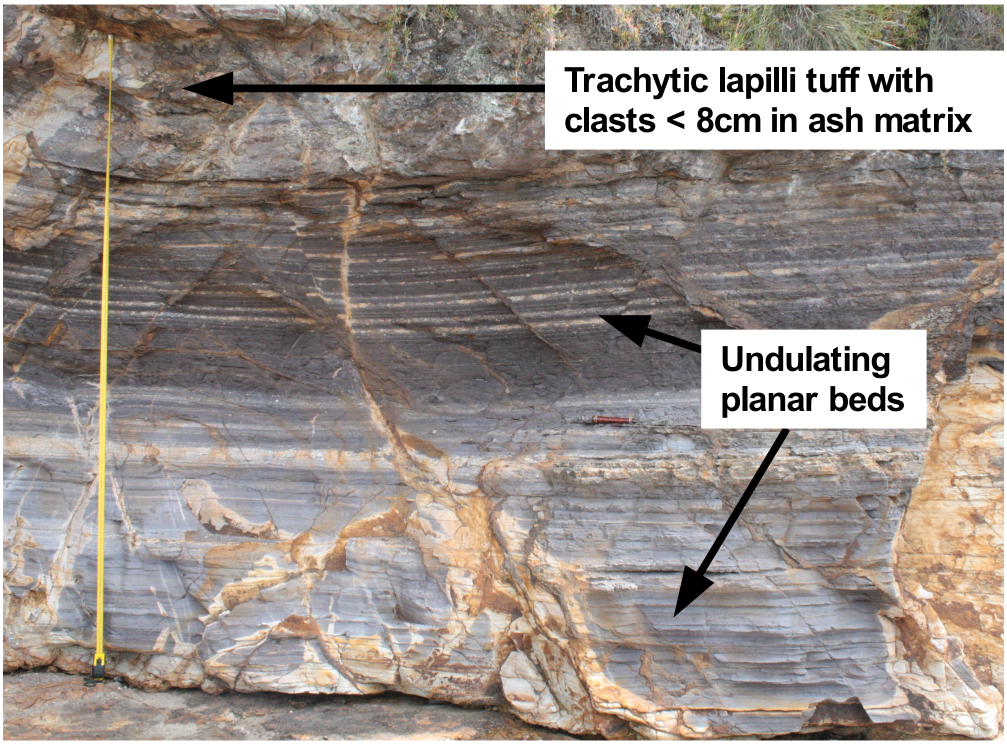


Fig 5.7 Outcrop of trachytic tuff exposed on the east coast of Onawe Peninsula showing planar beds with some ripple like structures

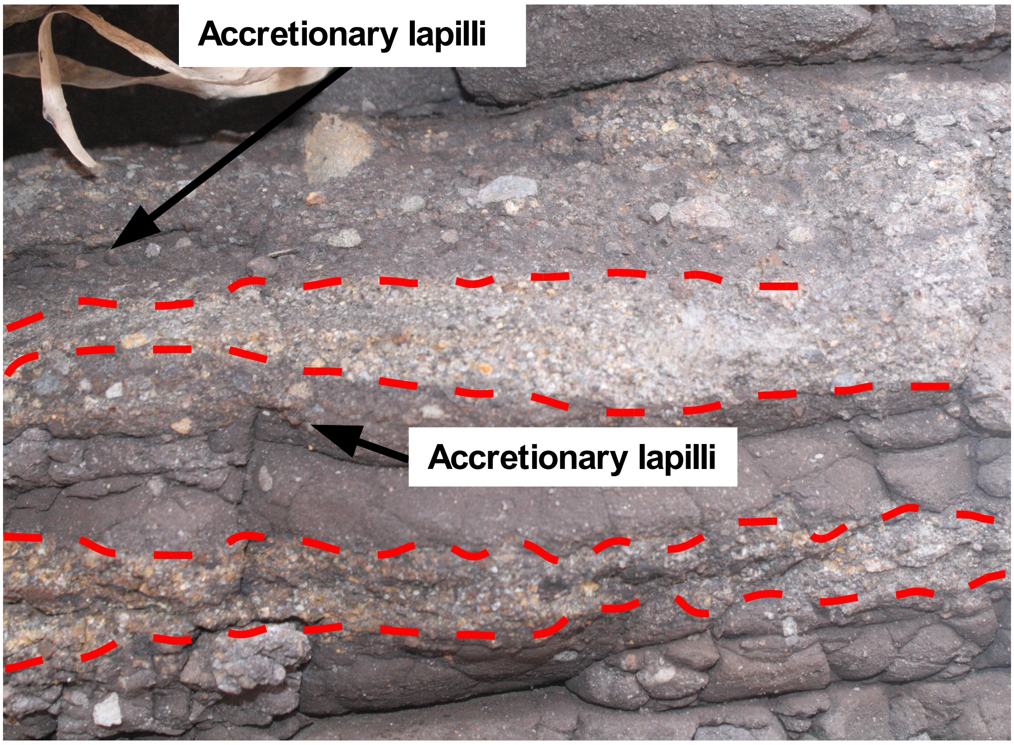


Fig 5.8 Close up of the trachytic tuff exposed on the east coast of Onawe Peninsula showing planar beds with pinch and swell structures and accreationary lapilli

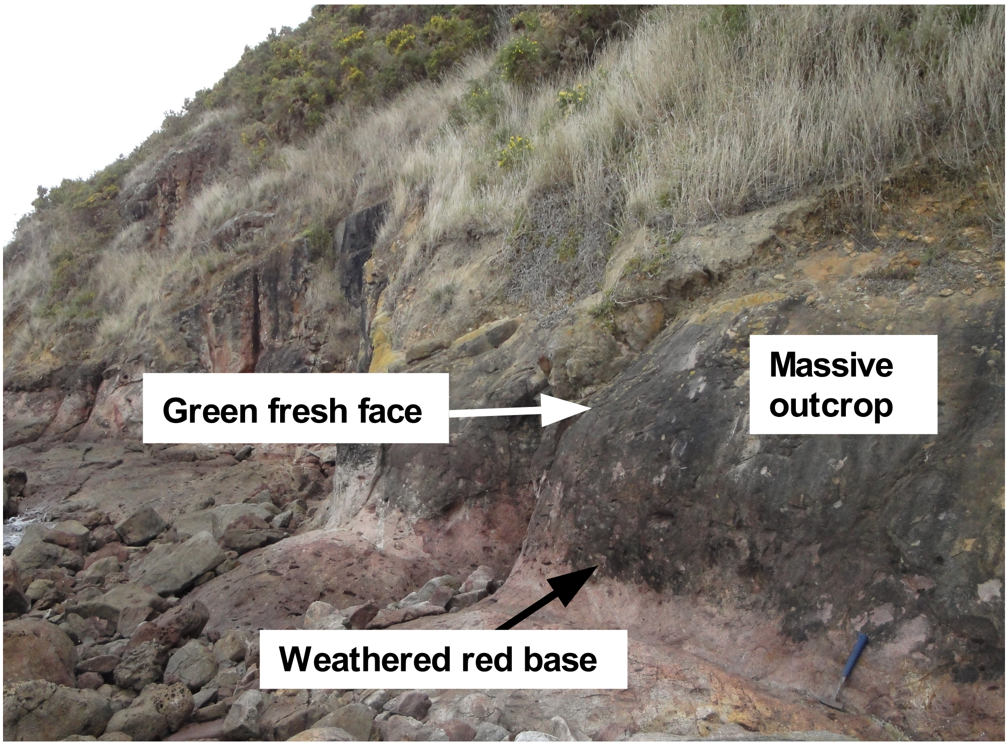


Fig 5.9 Outcrop of Tikao trachytic dome exposed between Petit Carenage Bay and Tikao Bay showing the massive fine grained nature of the deposit.

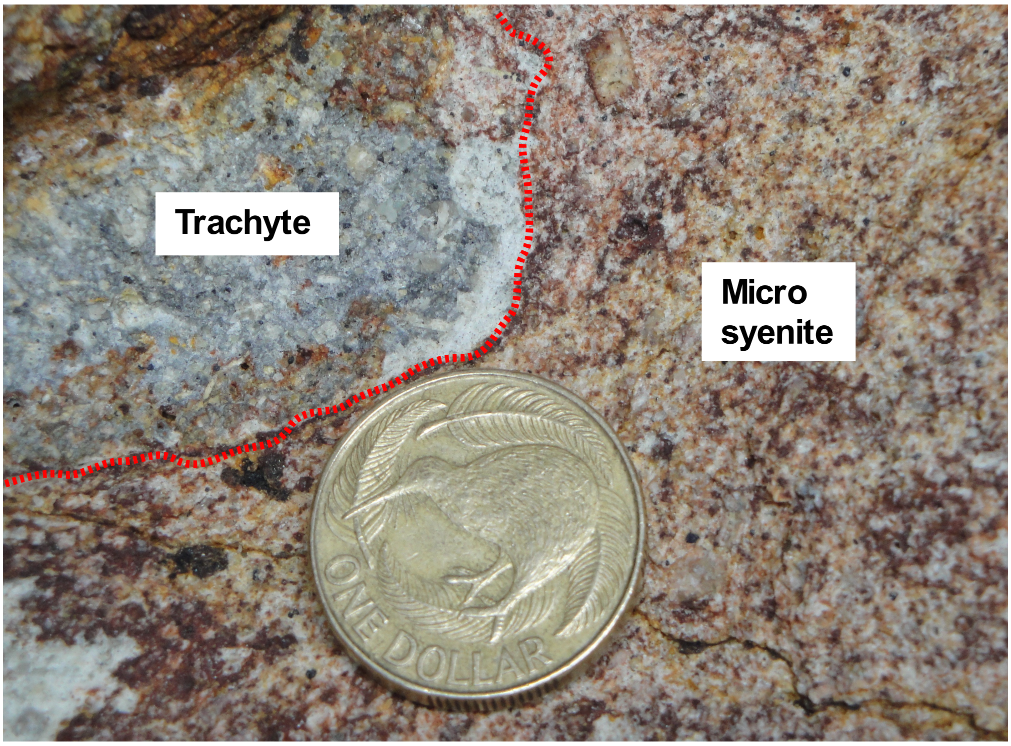


Fig 5.10 Outcrop of between Petit Carenage Bay and Tikao Bay of grey-white microsyenite including coarse grained aggregates of trachyte.

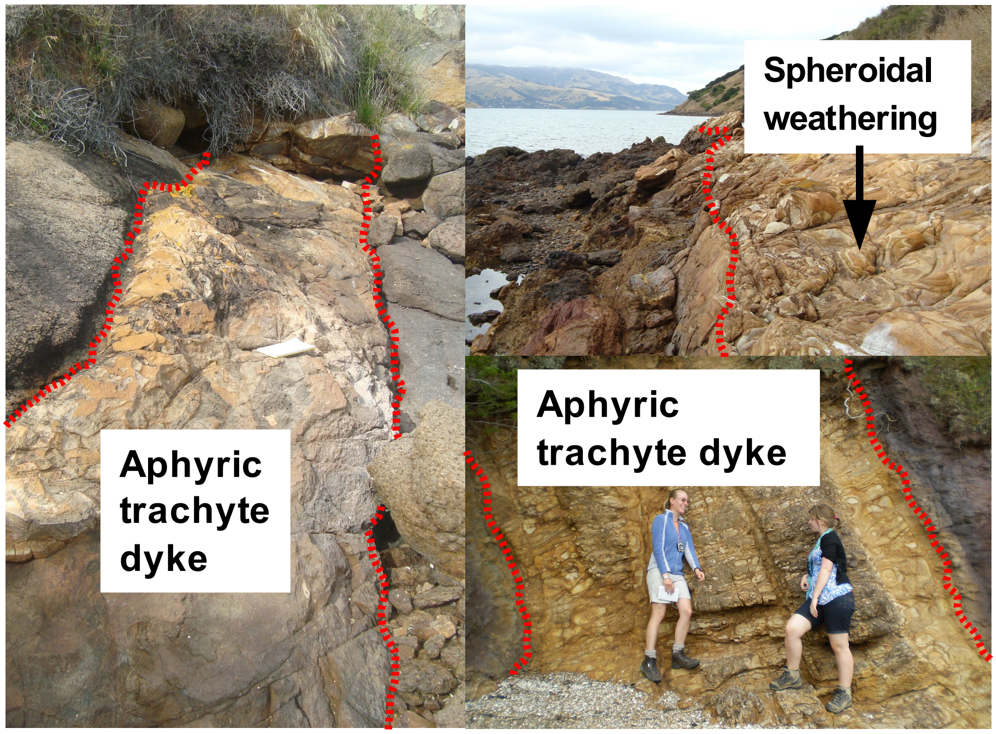


Fig 5.11 Type A dykes exposed around the shore platforms of Akaroa Harbour. Dykes are cream to tan, aphyric trachyte dykes that typically range from 0.5m to 6m in width

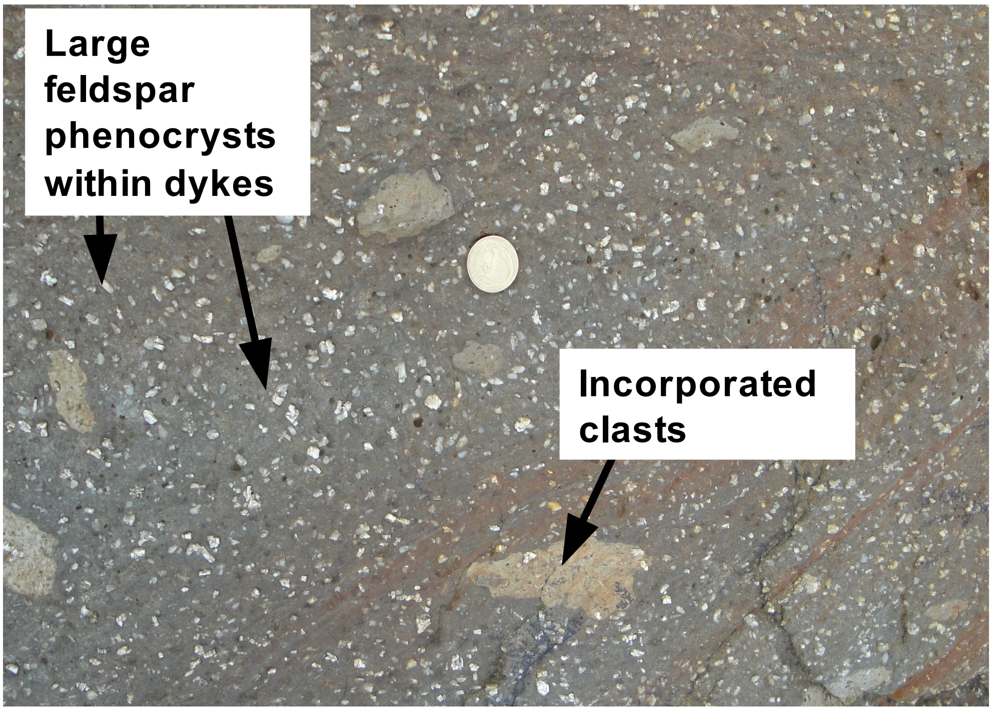
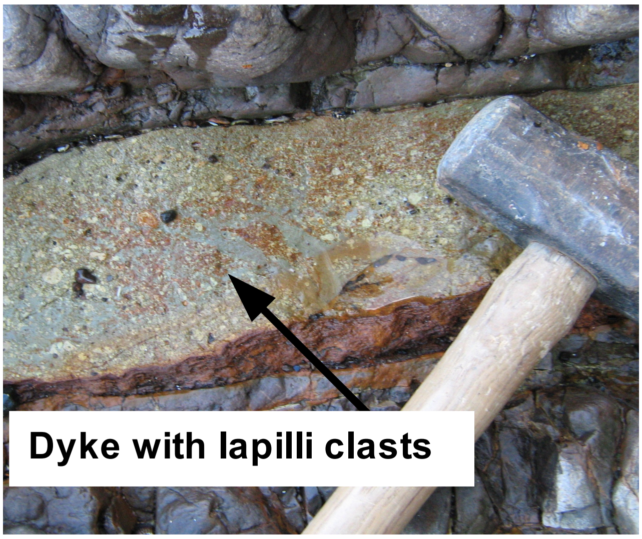


Fig 5.12 Close up of type b dyke. Dykes are comprised of porphyritic dark green trachyte containing euhedral phenocrysts < 15 mm. Occasional clast are incorporated



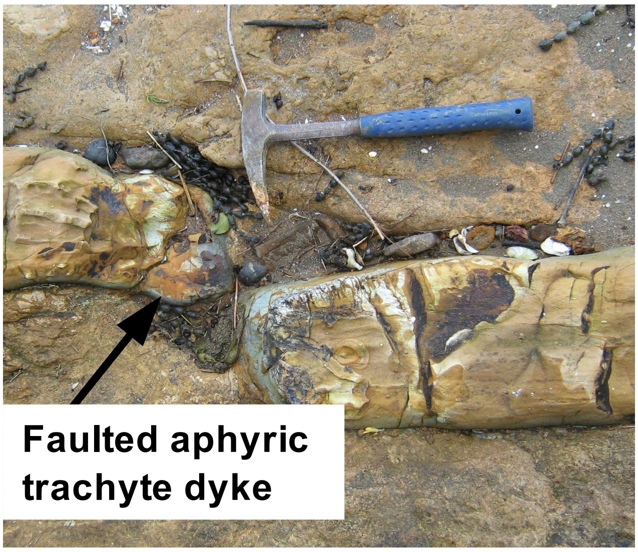


Fig 5.13a and b Type C dykes exposed around the shore platforms of Akaroa Harbour. Dykes are comprised of aphyric green trachyte**.**

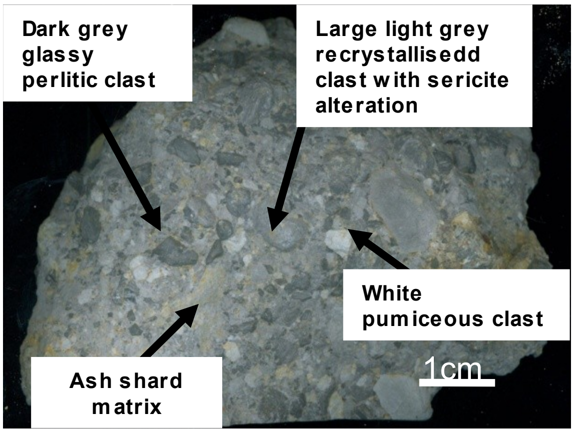


Figure 5.14a sample 3280 Hand sample shows a monomictic clast supported trachytic tuff breccia, with angular to surrounded, recrystallised dense clasts, glassy perlitic clasts and pumiceous clasts

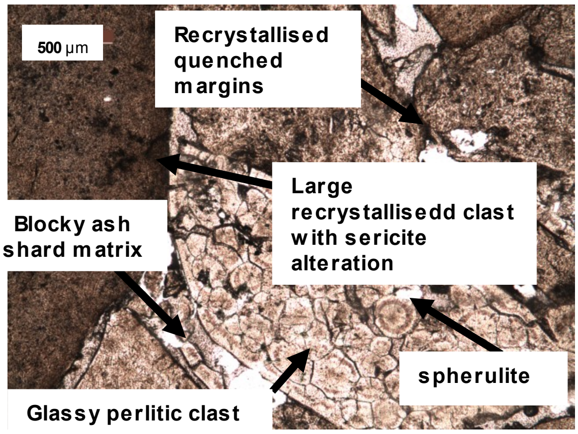


Figure 5.14b sample 3280 Photomicrograph of trachytic tuff breccia showing spherulites, perlite like textures in some glassy clasts, sericite alteration in dense clasts and altered quenched clast margins.

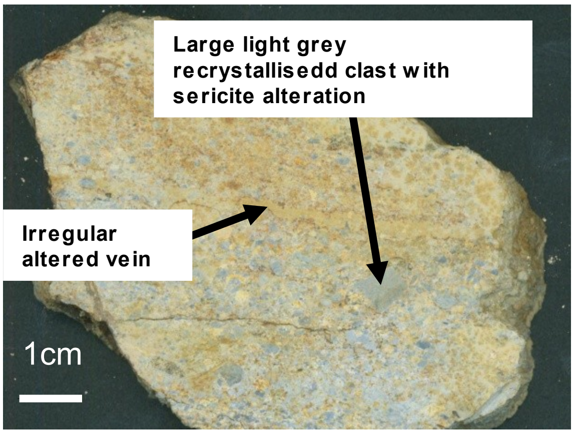


Figure 5.15 sample OPE-AT-02, Thin section 2 **a)** Hand sample shows a monomictic trachyte lapilli tuff with angular to sub-rounded dense trachyte, glassy perlitic clasts and pumiceous trachyte and ash sized matrix

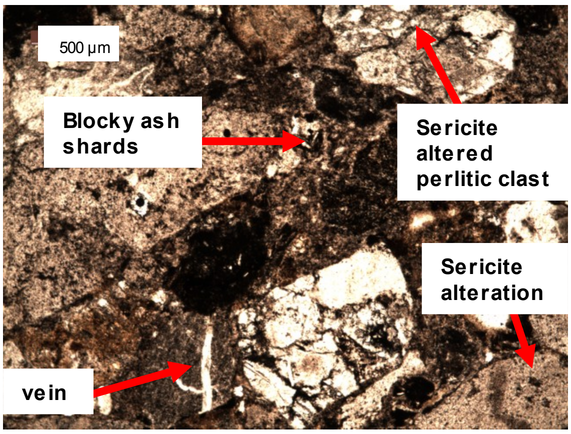


Figure 5.15 sample OPE-AT-02, thin section 2 **b)** Photomicrograph of trachyte lapilli tuff shows altered clasts with recrystalised quenched margins, glassy clasts have perlitic like textures and highly altered clasts are altered to sericite, the matrix consists of altered ragged to sub-rounded ash sized shards.

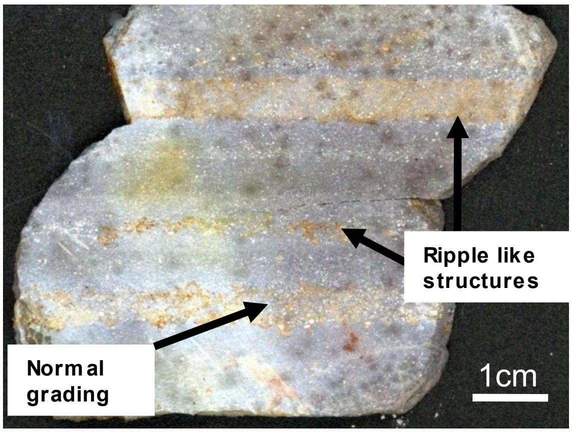


Figure 5.16a) sample EH-O-03, Thin section 5 sample shows a monomictic laminated trachyte tuff, comprised of fine to coarse ash sized shards. Normal grading is apparent with coarse grained layers showing some ripple like structures.

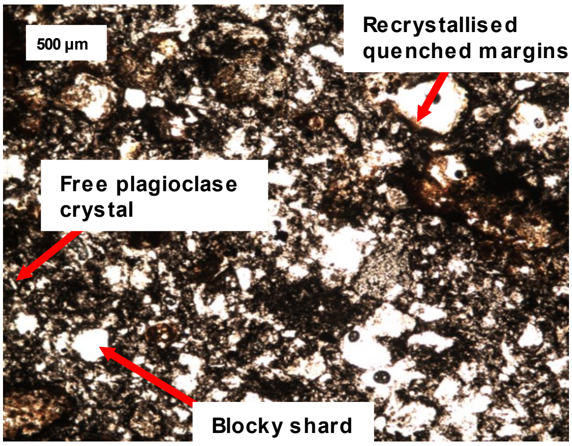


Figure 5.16b sample EH-O-03, Thin section 5 Photomicrograph of trachyte tuff shows dominantly blocky to sub-rounded ash sized shards, with some glass shards, pores and free crystals in coarser layers. Larger clasts have recrystalised quenched margins.

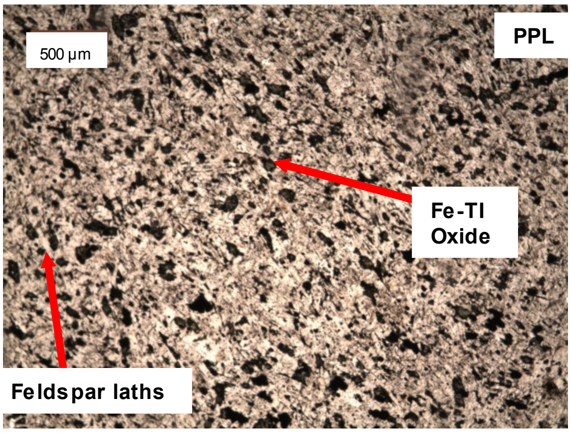


Figure 5.17a sample 3252. Photomicrograph of Trachyte lava from Tikao Dome in plane polarized light (ppl) shows an aphanitic and trachytic texture comprised of feldspars clinopyroxene and Fe-Ti oxides.

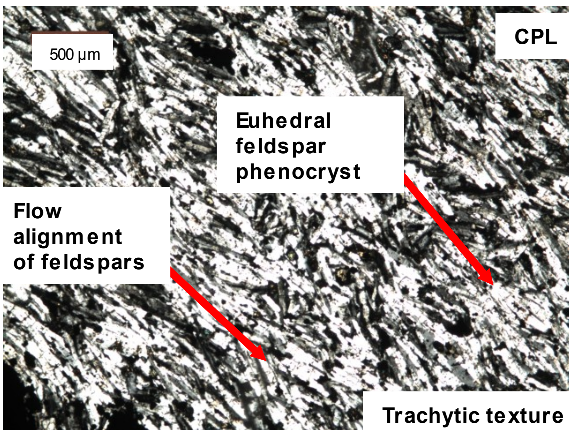


Figure 5.17b sample 3252 Photomicrograph of Trachyte lava from Tikao Dome in cross polarized light (cpl) showing flow alignment of feldspar laths and interstitial clinopyroxene and Fe-Ti Oxides forming an overall trachytic texture.

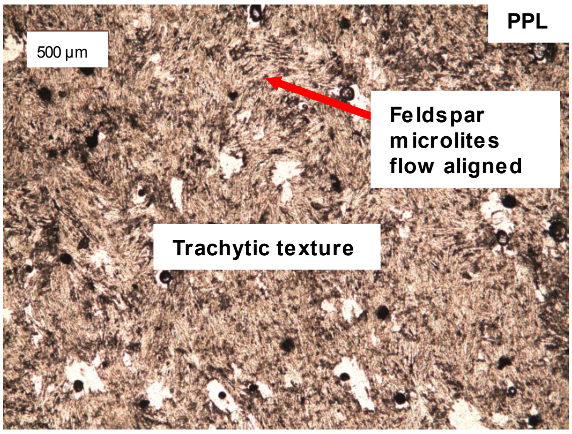


Figure 5.18a sample OPE-JG-03. Photomicrograph of a aphanitic trachyte dyke in PPL, comprised of feldspar with minor interstitial Fe-Ti oxides

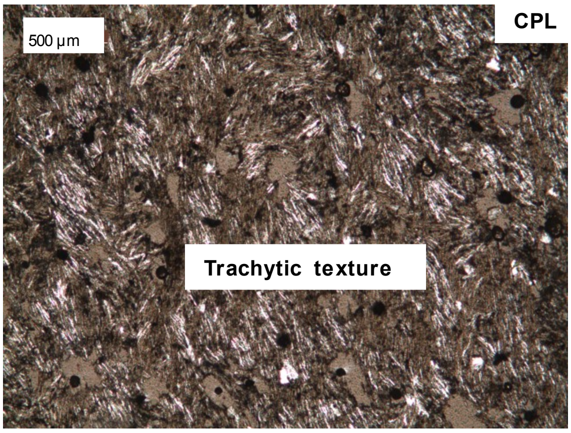


Figure 5.18b sample OPE-JG-03 Photomicrograph of a aphanitic trachyte dyke in CPL, showing trachytic texture with flow aligned feldspar microlites.

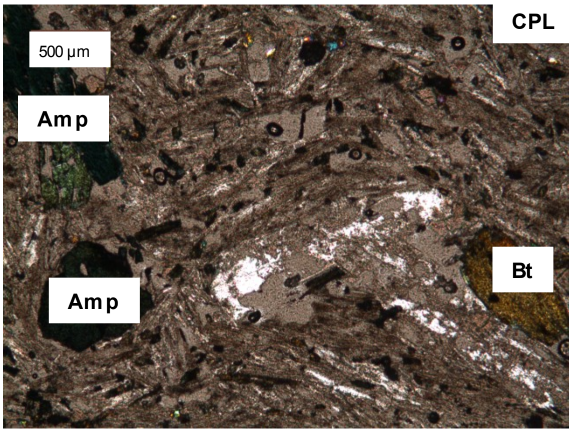


Figure 5.19a sample 3253 Photomicrograph of a porphyritic trachyte dyke in CPL showing phenocrysts of amphibole and biotite in a groundmass of feldspar laths and minor amounts of iron oxides and glass.

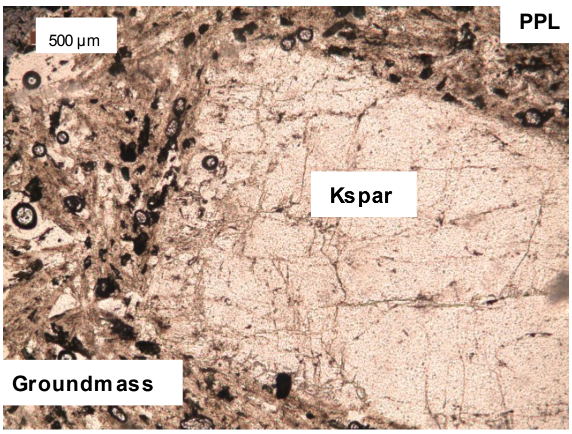


Figure 5.19b sample 3253 Photomicrograph if a porphyritic trachyte dyke in PPL showing a large phenocryst of alkali feldspar in a groundmass of feldspar clinopyroxene and Fe-Ti oxides.

5.4 Trachytic stratigraphic sequences from different localities

The following section describes complete trachytic stratigraphic sections located around the harbour. Refer to stratigraphic logs located in the figures section.

Onawe Peninsula (Stratigraphic log Fig 5.20 see appendix)

The stratigraphic sequence at Onawe Peninsula is a continuous sequence on the eastern side of the Peninsula (Fig 5.2 see appendix). The logged sequence begins on the southern end of Onawe Peninsula following an initial hawaiite flow of the Akaroa Harbour Formation (*ah*) and a sill that intruded the contact between the Harbour Formation and Lushington Breccia Formation (Fig 4.2). The sequence begins with a trachytic tuff breccia and continues north up through the whole Lushington Breccia Formation (*al*) sequence. The basal unit of the Lushington Breccia Formation exposed on Onawe Peninsula is ~ 1m of Trachytic tuff breccia (Fig 5.20 see appendix). The deposit has a blue grey ash matrix with solid sub-angular to sub-rounded, trachyte clasts up to 8 cm in size (Fig 5.20 see appendix)(Fig 5.21). A sharp contact is followed by ~1.4 m of alternating beds of laminated trachytic tuff and normal graded lapilli tuff (Fig 5.20 see appendix)(Fig 5.22)(Fig 5.6a). This unit grades into ~1.2m of brown, clast supported, massive, rubbly trachyte lapilli tuff (Fig 5.20 see appendix)(Fig 5.6a). A sharp contact is followed by 30 cm of trachytic tuff with a single clast supported layer of trachyte lapilli tuff. Followed by a normal graded trachytic lapilli tuff to trachyte tuff (Fig 5.20 see appendix) with rare basaltic bombs, the bedding of this unit is 92/10N (Fig 5.6a) (Fig 5.6b). A sharp irregular contact dipping to the north marks the change into a ~ 30 cm thick deposit of large trachytic clasts (< 8cm) in a blue grey ash matrix (Fig 5.20 see appendix)(Fig 5.23). This unit is followed by ~90 cm of weakly bedded bluish grey, indurated, trachyte tuff with intermittent layers of accretionary lapilli and white coarse ash beds (Fig 5.7) (Fig 5.20 see appendix). Which grades into 40cm of inter-bedded layers of bluish grey, laminated trachytic tuff and lapilli tuff. This unit grades into > 70cm of blue to cream, matrix supported trachyte lapilli tuff (Fig 5.20 see appendix). Clasts are < 5 cm in size and consist of sub-angular to sub-rounded dense trachyte clasts and occasional pumiceous and flow banded clasts.

Figure 5.21 Field photograph of the trachytic tuff breccia exposed on Eastern Onawe Peninsula. The deposit consists of blue grey ash matrix with solid sub-angular to sub-rounded, trachyte clasts up to 8 cm in size

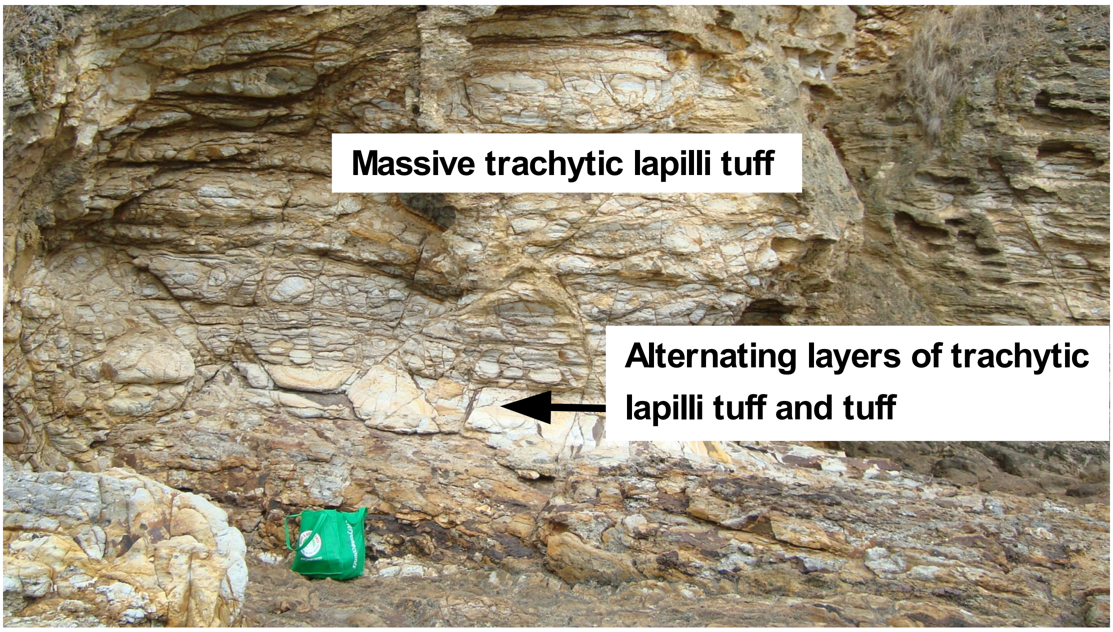


Figure 5.22 Field photograph of the trachytic lapilli tuff exposed on Eastern Onawe Peninsula. The deposit consists interbedded layers of trachytic lapilli tuff and tuff. The upper section of this unit consist of a massive rubbly clast supported trachytic lapilli tuff.

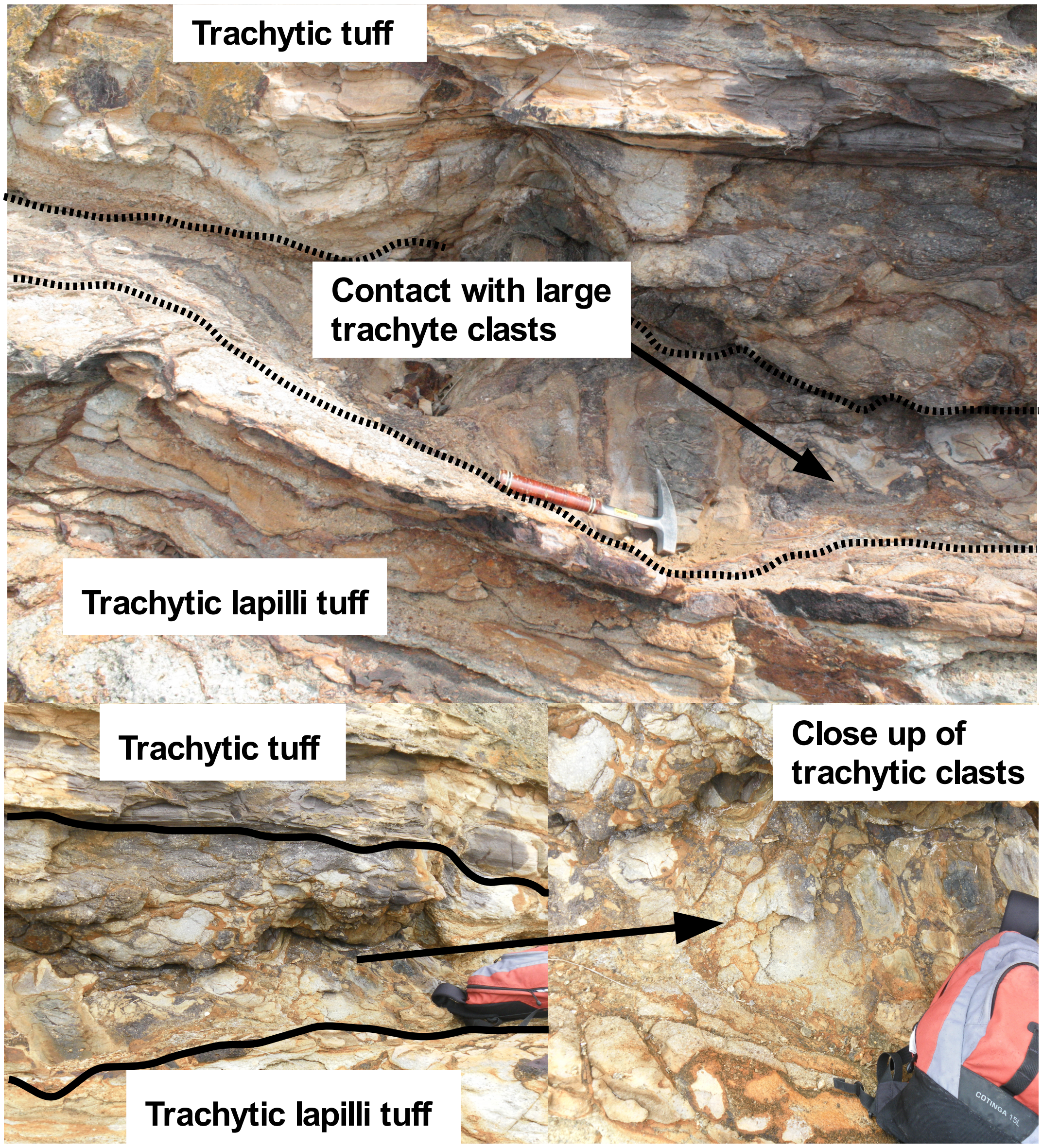


Figure 5.23 Field photograph of the contact between the trachytic lapilli tuff and tuff exposed on Eastern Onawe Peninsula. The contact is sharp and irregular dipping to the north. The contact is marked by a 30cm thick deposit of large trachytic clasts (< 8cm) in a blue grey ash matrix.

Lushington Bay to Takamatua Bay (Stratigraphic log Fig 5.24 see appendix)

The stratigraphic sequence of the Lushington Breccia Formation (*al*) between Lushington and Takamatua Bay (Fig 5.2 see appendix) begins with a basal unit of ~9.4 m of trachytic tuff breccia (Fig 5.24 see appendix). The deposit has sub-angular to sub-rounded 2 - 40 cm trachyte clasts in a bluish grey ash matrix (Fig 5.4). The unit grades into 3 m of alternating beds of thin (20cm) deposit of trachytic tuff and thicker (70cm – 1m) beds of trachytic tuff breccias (Fig 5.24 see appendix). The trachytic tuff beds consist of intermittent trachyte lapilli (2 mm to 5 cm) in a bluish grey ash matrix, while the trachytic tuff breccia consists of trachyte clasts (2 - 20 cm) in a bluish grey ash matrix (Fig 5.24 see appendix) (Fig 5.5). A white trachytic sill intrudes the contact between the next unit, therefore the relationship between the units is unknown but is likely conformable and gradational. The next unit consist of 70cm of alternating beds of normally graded trachyte lapilli tuff and laminated trachyte tuff (Fig 5.24 see appendix). The top the unit is overlain by a porphyritic mafic lava flow that has been intruded by another trachytic sill. The whole sequence dips 182/10 to the east (Fig 5.25).

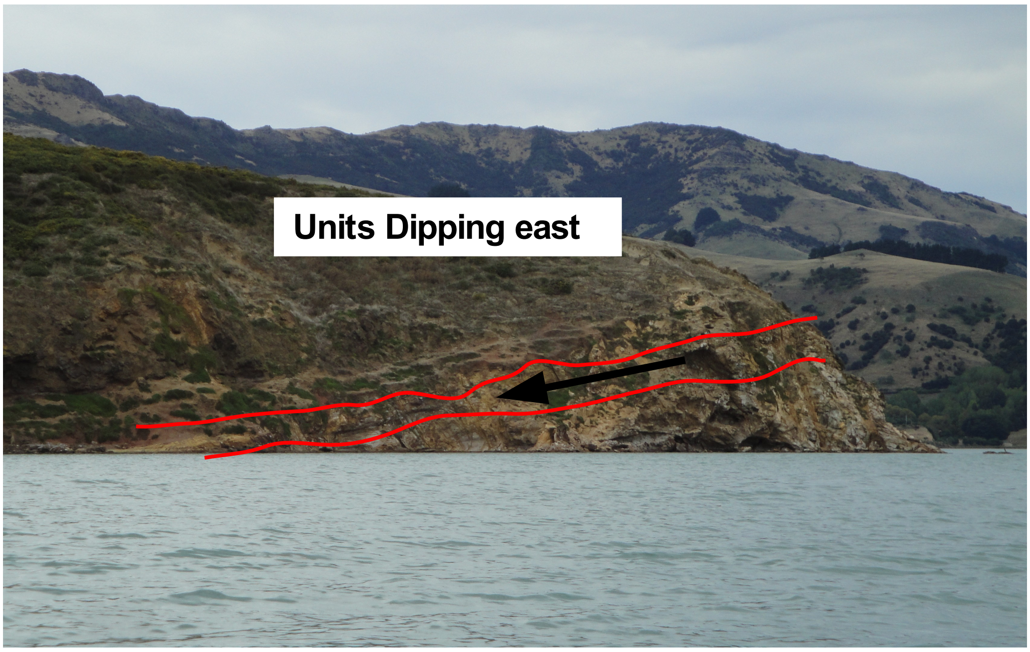


Figure 5.25 Field photograph of the Lushington Breccia Formation at its type locality, Lushington Bay. The whole sequence dips 182/10 to the east.

French Farm to Barrys Bay (Stratigraphic log Fig 5.26 see appendix)

The stratigraphic sequence exposed along a road cut between French Farm and Barry's Bay (Fig 5.2 see appendix) is a ~7 m section of the Lushington Breccia Formation (*al*). The logged section begins with a basal unit of 2.2 m of trachyte tuff breccia (Fig 5.26 see appendix). Clasts consist of 3 – 10 cm, angular to sub-rounded solid juvenile trachyte in a blue grey ash matrix. The upper contact of this unit is gradational, transitioning into a unit of alternating beds of trachyte lapilli tuff and trachyte tuff (Fig 5.26 see appendix). The upper contact of this unit is sharp followed by a 60 cm deposit of trachyte tuff breccia, with 3 – 10 cm clasts of solid juvenile trachyte in an ash matrix (Fig 5.26 see appendix). This unit grades into ~ 1 m of coarser trachytic tuff breccia, with 5 -10 cm clasts of solid juvenile trachyte in a bluish grey ash matrix (Fig 5.26 see appendix). Half way through the breccia unit is a thin ~10cm lapilli tuff. The upper contact of the breccia is topped by a fine 10 cm ash layer with a sharp upper contact. The next unit consist of 30 cm of alternating beds of trachyte lapilli tuff and trachyte tuff (Fig 5.26 see appendix). The lapilli tuff consists of 5 mm – 5 cm trachyte clasts in an ash matrix. A sharp contact separates the next unit which consists of 20 cm of trachyte lapilli tuff with clast sizes between 2 – 6 cm (Fig 5.26 see appendix). A thin ash horizon separates the previous unit from the following ~0.5 m of alternating beds of trachyte lapilli tuff and trachyte tuff. The top contact is gradational in nature and the lapilli tuff shows normal grading into a 40 cm deposit of well sorted, laminated, trachyte tuff (Fig 5.26 see appendix).

French Farm to Petit Carenage Bay (Stratigraphic log Fig 5.27 see appendix)

The stratigraphic sequence exposed between French Farm and Petit Carenage Bays is a 3.4 m section of the Lushington Breccia Formation (*al*) (Fig 5.2 see appendix) (Fig 5.27 see appendix). The sequence begins with a basal unit of 40 cm of bluish grey trachyte lapilli tuff with 2 mm - 2 cm clasts of solid trachyte in an ash matrix (Fig 5.27 see appendix). This unit grades into 2 m of bluish grey trachyte tuff breccia, consisting of 2 -25 cm angular – sub-rounded clasts of solid trachyte in an ash matrix (Fig 5.27 see appendix). This unit grades into a finer 40cm deposit of trachyte lapilli tuff, clasts are typically angular to sub-rounded, 2 -5 cm solid trachyte clasts in an ash matrix. This unit has weakly developed bedding recorded as 090/10NW. The remainder of the sequence consists of alternating beds of Trachyte tuff breccias and trachyte lapilli tuff (Fig 5.27 see appendix).

5.5 Fence diagram (Fig 5.28 see appendix)

The fence diagram of the trachytic units of the Lushington Breccia Formation (*al*) shows the correlation of units across the harbour. These correlations were developed by comparing stratigraphic logs, lithologic descriptions and structural measurements collected in this study.

5.6 Mafic pyroclastics and lava flows

The mafic units of the emergent and early phases of Akaroa Volcano belong to the Harbour Formation (*ah*) and the French Hill Formation (*af*). These deposits occur along shore platforms and sea cliffs of the inner harbour (Fig 5.2 see appendix). The Harbour Formation is the earliest unit on Akaroa Volcano representing the first subaerial volcanism. This formation is only exposed on Onawe Peninsula as a singular southernmost lava flow (Fig 5.2 see appendix) (Fig 4.2). The French Hill Formation deposits were formed during and following a phase of trachytic eruptions and are the start of the main shield building stage. The French Hill Formation is an extensive unit which consists of lava flows, welded tuffs, cinder cones and phreatomagmatic deposits (Fig 5.2 see appendix).

Harbour Formation

Hawaiite flows

Hawaiite flows are the earliest subaerial lava flows of Akaroa Volcano, but also occur later in the French Hill Formation (*af*). Hawaiite flows are porphyritic to aphanitic blue-black, well indurated flows with phenocrysts (< 10mm) of plagioclase and olivine. The hawaiite lava flow of the Harbour Formation (*ah)* occurs on the eastern coast of Onawe Peninsula on its southern end (Fig 5.2 see appendix). This flow is a porphyritic blue-black lava flow exposed on the shore platform (Fig 4.2). The top and bottom contacts of this unit are obscured by a dyke and sill, therefore the nature of the contacts is unknown (Fig 4.2). However, age the relationships are apparent as the unit is stratigraphically bellow the Lushington Breccia Formation (*al*).

Thin section

The hawaiite lava flow of the Harbour Formation (*ah)* formation (OPE-JG-08) is a holocrystalline, porphyritic and seriate textured flow (Fig 5.29a) (Fig 5.29b). Phenocrysts are low in abundance < 10%, they are typically 1- 10mm in size and consist of euhedral to subhedral olivine (~4%) and plagioclase (~6%) (Fig 5.29a)(Fig 5.29b)(Table 5.3). The groundmass has a seriate texture; therefore various grain sizes occur all of which are < 0.5 mm (Fig 5.29a)(Fig 5.29b)(Table 5.3). The groundmass consists of ~52% plagioclase, ~23% clinopyroxene, ~9% Fe-Ti oxides and ~6% olivine (Fig 5.29a)(Fig 5.29b)(Table 5.3). Plagioclase phenocrysts are complexly zoned and some have spongy cellular cores, while olivine phenocrysts are often pseudomorphed by calcite (Fig 5.29a)(Fig 5.29b)(Table 5.3).

Welded polylithic lapilli Tuff

A welded polylithic lapilli tuff conformably overlies the Harbour Formation lava flow on the west side of Onawe Peninsula (Fig 5.2 see appendix). The deposit consists of a dark grey to black, poorly sorted, welded lapilli tuff. Clasts range in size from < 1 mm to 15 mm, are angular to sub-rounded, and are welded by greyish black fresh glassy basaltic lava (Fig 5.30a) (Fig 5.30b). Clast lithologies are diverse and include basaltic to trachytic lavas, mudstones and sandstones (Fig 5.30b). Two distinct packages are apparent: one is fine grained (clasts < 5mm in diameter) and the other is coarse grained (clasts 5 -15mm diameter) and rich in mudstone and sandstone lithics (Fig 5.30b). The contact between these units is gradational and irregular.

Thin section descriptions 3140

The welded polylithic tuff is poorly sorted, consisting of fine to coarse (~0.4 – 10 mm) rounded to sub-angular clasts welded together with minor amounts of basaltic glass (~10%) (Fig 5.30c)(Fig 5.30d) (Table 5.4). The majority (~59%) of clasts consist of various lavas, these are mostly basaltic in composition. Aphyric, porphyritic and pilotaxitic textures occur (Fig 5.30c) (Fig

5.30d). Other clasts consist of plagioclase fragments (~1%), quartz arenite fragments with ~0.04 mm grain size (~5%), mudstone (tr), course grained (0.2mm) quartz-arenite fragments (~10%) and ~25% of poorly developed cordierite (Fig 5.30c)(Fig 5.30d)(Table 5.4). Some of the quartz-arenite fragments are partially recrystallised to tridymite and chlorite and occur as finer cryptocrystalline clasts (Fig 5.30c)(Fig 5.30d)(Table 5.4).

French Hill Formation

Picritic Basalt

Picritic flows occur in the early shield building stage of Akaroa Volcano, and constitutes part of the French Hill Formation (*af*). The flows consist of blue black, well indurated and porphyritic picritic basalt containing phenocrysts < 10 mm in size of olivine, clinopyroxene and plagioclase.

Thin section description

Picritic basalts of the French Hill Formation (OPW-JG-12, HP-EH-02) are holocrystalline, displaying porphyritic and seriate textures (Fig 5.31a)(Fig 5.31b). Phenocrysts abundances are typically less than 30%, consisting of 1- 9 mm in size euhedral to subhedral olivine (~13 %) clinopyroxene (~6%) and plagioclase (tr) (Fig 5.31a)(Fig 5.31b)(Table 5.3). The groundmass has a seriate texture so various grain sizes occur all < 0.5 mm. The groundmass consists of ~42% plagioclase, ~23% clinopyroxene, ~12% Fe-Ti oxides and ~4% olivine (Fig 5.31a)(Fig 5.31b)(Table 5.3). Plagioclase phenocrysts are complexly zoned and some have spongy cellular cores, olivine phenocrysts are often pseudomorphed by calcite (Fig 5.31a)(Fig 5.31b)(Table 5.3).

Olivine Alkali Basalt

Olivine Alkali Basalt flows occur in the early shield building stage of Akaroa Volcano and make up part of the French Hill Formation (*af*). Olivine alkali basalt flows are blue black, well indurated and porphyritic with phenocrysts of plagioclase (< 6mm) and olivine (< 2 mm).

Thin section description

The Olivine Alkali Basalts of the French Hill Formation (*af*) (OPW-EH-01) are holocrystalline, displaying porphyritic and seriate-textures. The flows contain plagioclase and olivine and rare magnetite phenocrysts (< 10%) within a fine-grained, intergranular groundmass (Fig 5.32a) (Fig 5.32b)(Table 5.3). Plagioclase phenocrysts and microphenocrysts are complexly zoned and range in size up to 6 mm. Commonly larger plagioclase phenocrysts have spongy cellular cores. Olivine phenocrysts are euhedral to subhedral and are typically < 2mm in size. Amygdoidal or vesicular textures are present in some basalts, amygdales (< 5 %) are often infilled with fine crystals of calcite and/or zeolites. The groundmass consists of feldspar laths, clinopyroxene, olivine and spinel (Fig 5.32a)(Fig 5.32b)(Table 5.3). Coarser grained alkali basalts (< 2mm) have multiple zoned plagioclase phenocrysts and also display intergranular and subophitic textures with interstitial oikocrysts of clinopyroxene encasing plagioclase and olivine microcrystals (Fig 5.32a)(Fig 5.32b) (Table 5.3).

Mugearite and Benmoreiite lava flows

Mugearite and Benmoreiite lavas flows occur in the early shield building stage of the French Hill Formation (*af*). Lavas are mostly aphanitic and aphyric; however trace amounts of complexly zoned plagioclase phenocrysts are occasionally present. These phenocrysts often have disequilibrium textures and resorbed cores The groundmass consists of large amounts of Fe-Ti oxides, clinopyroxene, olivine and feldspars.

Thin section description

A mugearite flow exposed on Onawe Peninsula (OPE-EH-01) is a holocrystalline, aphanitic textured flow (Fig 5.2 see appendix). Only trace amounts of feldspar phenocrysts are present, these are ~2mm in size and euhedral in shape. The groundmass has an average grain size of < 0.2 mm and consists of ~52% feldspar, ~23% clinopyroxene, ~20% Fe-Ti oxides, ~2% olivine and ~3% apatite

(Fig 5.33a)(Fig 5.33b)(Table 5.3).

Brecciated basaltic lapilli Tuff

Brecciated basaltic lapilli tuff occurs as the basal unit of many scoria cones within the French hill formation. Well developed brecciated basal units occur in scoria cones at North Onawe Peninsula, Robinsons Bay and Anchorage Bay (Fig 5.2 see appendix). Deposits consist of highly brecciated yellow – red brown lapilli tuff with accretionary lapilli (Fig 5.34a)(Fig 5.34b). Deposits are highly altered and fractured with abundant palagonitisation and ragged 1 – 4 mm clasts in a fine ash matrix (Fig 5.34a)(Fig 5.34b).

Thin section descriptions

Brecciated basaltic lapilli tuff (OPE-AT-01) consists of a fine ash (1/8 – 1/4 mm) with 1 - 4 mm fine lapilli (Fig 5.34c)(Table 5.4). The deposit is matrix supported and clasts range in angularity between sub- angular to sub-rounded. The deposit is entirely juvenile made up of 75% ash, 20% altered vesicular clasts that are elongated and ragged in nature and 5% accretionary lapilli (Fig 5.34c) (Table 5.4).

Spatter deposits

Spatter deposits occur throughout the French Hill Formation (*af*) as discrete spatter cones or as eruptive packages of cinder cones found on mid and north Onawe Peninsula, Hammond Point, Robinsons Bay, Childrens Bay and Anchorage Bay (Fig 5.2 see appendix). Deposits consist of welded reddish grey, well bedded, fine to medium basaltic ash with elongate spatter and ribbon bombs (Fig 5.35a).

Thin section

Spatter (RB-AT-03) consists of scoriaceous elongate spatter clasts (~1 cm) in a matrix of glass shards (1/4 mm). The deposits are moderately sorted and consist of angular ragged glass shards and sub-angular to sub-rounded elongate flattened scoria clasts. The deposits are entirely juvenile with ~ 60% flattened scoria and ~ 40% glass shards (Fig 5.35b)(Fig 5.35c)(Table 5.4).

Mixed scoriaceous deposits (partially flattened)

Mixed scoriaceous deposits, occur throughout the French Hill Formation (*af*) as units in discrete scoria cones. Cones are found at mid and north Onawe Peninsula, Hammond Point, Robinsons Bay, Childrens Bay and Anchorage Bay (Fig 5.2 see appendix). Deposits consist of brownish red, well bedded, fine to medium basaltic ash with basaltic scoria and lava bombs (Fig 5.36a). Bomb morphologies include ribbon spindle and cow dung bombs and range between large lapilli (5cm) and bomb size (30 cm) (Fig 5.36a).

Thin section descriptions, OPW-JG-09 transitional

Scoriaceous lapilli tuff with bombs is a fine to medium ash (1/4- 1/2 mm) with lapilli (~1cm) and bombs. The deposits are matrix supported and clasts are sub-angular to sub-rounded ragged shards to sub-rounded clasts. The deposits are juvenile, and clast lithologies consist of, ~ 40% scoria in an ash matrix (~60%) (Fig 5.36b)(Fig 5.36c)(Fig 5.36d) (Table 5.4) . Rare plagioclase phenocrysts occur in crystalline basalt; however, microcrystals of plagioclase laths with alignment are more common. Flattened scoria clasts are abundant and have characteristic elongate vesicles (Fig 5.36b)(Fig 5.36c).

Non flattened Scoriaceous deposits

Non flattened scoriaceous deposits occur throughout the French Hill Formation (*af*) as units within discrete scoria cones. Cones are found at mid and north Onawe Peninsula, Hammond Point, Robinsons Bay, Childrens Bay and Wainui Bay (Fig 5.2 see appendix). Deposits consist of brownish red, well bedded, fine to medium basaltic ash with basaltic scoria and lava bombs (Fig 5.37). Bomb morphologies are dominantly non flattened breadcrust and spindle bombs and range in size from small lapilli (~5 mm) to bomb size (<40cm) (Fig 5.37).

Thin section descriptions (RB-AT-02 TS21)

Scoriaceous lapilli tuff with bombs is a fine to medium ash (1/4- 1/2 mm) with lapilli (~1cm) and bombs (Table 5.4). The deposits are matrix supported and clasts are sub-angular to sub-rounded ragged shards to sub-rounded clasts. The deposits are juvenile and clast lithologies consist of ~ 60% crystalline basalt, ~20% scoria, in an ash matrix (~20%) (Table 5.4). Rare plagioclase phenocrysts occur in crystalline basalt; however, microcrystals of plagioclase laths with alignment are more common.

Ash rich deposits

Ash rich deposits occur throughout the French Hill Formation (*af*) often as the uppermost unit of discrete scoria cones. Cones are found at mid and north Onawe Peninsula, Hammond Point, Robinsons Bay, Childrens Bay and Anchorage Bay (Fig 5.2 see appendix). Deposits consist of brownish red, well bedded, fine to medium basaltic ash with well sorted lapilli spatter (~3 – 5 cm) (Fig 5.38). No thin sections of this layer were analysed as deposits were too weathered.

Formation	Thin section number	Rock Type	Texture	Grain size (Average)	Grain size (max)	Crystal shape	Pcrysts	GM	Other structures
af	OPW-JG-12	***Picritic basalt (Flow)***	Porphyritic & seriate	<1 mm	1- 9 mm	Euh - sub	Ol 13% Cpx 6% Pl tr	Pl 42%, Cpx 23%, Ol 4%, Fe-Ti Oxides 12%	Cpx twins, sector zoning, marginal overgrowth on discrete dissolution surfaces. Some poikilophitic Cpx encase equant Ol &/or pl. Ol pcryst altered to iddingsite on concoidal fractures and throught Ol microlites. Pl micropcrysts have spongy cellular cores with overgrowths of pl.
af	HP-EH-02	***Picritic basalt (Dyke)***	Porphyritic & seriate	<1 mm	1- 9 mm	Euh - sub	Cpx 17% Ol 13% Pl tr	Pl 36% Fe-Ti Oxides 20% Cpx 9%, Ol 5%	Cpx twins, sector zoning, marginal overgrowth on discrete dissolution surfaces. Some poikilophitic Cpx include equant Ol &/or pl. Ol pcryst altered to iddingsite on concoidal fractures and throught Ol microlites. Pl micropcrysts have spongy cellular cores with overgrowths of pl
af	OPW-EH-01	***Alkali Basalt (Flow)***	Porphyritic & seriate	<1 mm	< 6mm	Euh - sub	Pl 3%	Pl 54%, Cpx 26% Fe-Ti oxide 10%, Ol 7%	Pl phenocrysts multi zoned some have a spongy cellular cores. Pl shows intergranular and Sub ophitic textures with interstial oikocrysts of CPX inclosing PL & OL micro crystals
ah	OPE-JG-08	***Hawaiite (Flow)***	Porphyritic & seriate	< 0.5mm	1 -10 mm	Euh - sub	Ol 4% Pl 6%	Pl 52%, Cpx 23% Fe-Ti oxide 9%, Ol 6%	pcryst of Ol pseudomorphed by calcite, complexly zone PL with some spongy celular cores
af	OPW-JG-06	***Hawaiite (Flow)***	Porphyritic & seriate	<1 mm	1- 6 mm	Euh - sub	Pl 5% Ol 4%	Pl 43%, Fe-Ti Oxide 23%, Cpx 20%, Ol 5%	Pl pcrysts larger than Ol, pcrysts multizoned some have spongy cellular cores, sphrelites present
af	OPE-EH-01	***Mugearite (Flow)***	Aphanitic	<0.2 mm	2 mm	Euh- sub	Fs 1%	Fs 52%, Cpx 23% Fe-Ti oxide 20% Ap 3%, Ol 2%	Fs Pcryst elongate tabular

Table 5.3 Representitive thin section descriptions and modal mineral counts of effusive and intrusive mafic units

Abbreviations: Euh euhedral, Sub subhedral, Pcryst phenocrysts, Ol olivine, Pl plagioclase, Fs feldspar, CPX clinopyroxene, Ap Apatite, tr trace amounts

Formation	Sample No.	Rock Type	Grain size (Average)	Grain size (max)	Sorting	Clast or matrix supported	Angularity	clast shapes	Composition	Other structures
ah	3140	***Welded polylithic lapilli Tuff***	0.4 - 1 mm	15 mm	poor	matrix	rounded - sub-angular	blocky	60% juvenile, 40% lithics Lavas 50%, Pl 1%, mudstone 5%, quartz-arenite 10%, corderite 25%, basaltic glass 10%	
af	OPE-AT-01 Ts 12	***Brecciated basaltic lapilli Tuff***	1/8 - 1/4	1 - 4 mm	mod	matrix	sub-angular subrounded	elongate and ragged shards	20% altered vesicular clasts, 75% ash shards 5% accretionary lapilli	
af	RB-AT-03 Ts 18	***Spatter tuff***	1/4 mm	1 cm	mod	matrix	angular - sub-rounded	ragged glass shards, elongate flattend scoria	flattend scoria 80%, glass shards 20%	elongate vesicles in flattend scoria clasts
af	RB-AT-02 Ts 21	***Scoriacious Lapilli tuff with bombs***	1/4 - 1/2 mm	1 cm	mod	matrix	sub angular - subrounded	ragged shards - subrounded	crystaline basalt 60%, scoria 20%, ash 20%	Pl lath allignment
af	OPW-JG-09	***Scoriacious Lapilli tuff with bombs***	1/4 - 1/2 mm	6 mm	mod	matrix	sub angular - subrounded	ragged shards - subrounded	scoria 40% ash shards 60%	

Table 5.4 Representitive thin section descriptions and modal clast counts of pyroclastic mafic units

Abbreviations: Mod Moderate, Pl plagioclase

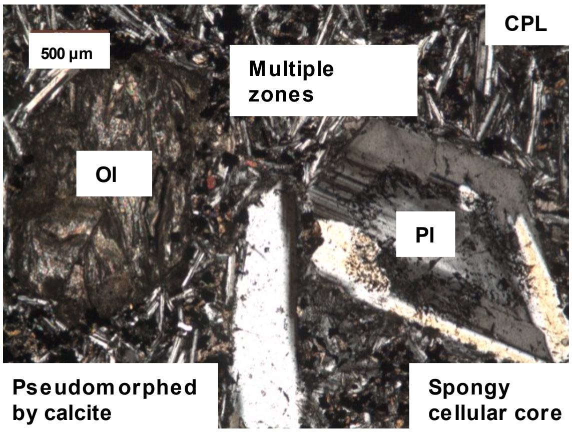


Figure 5.29a sample OPW-JG-06. Photomicrographs of a porphyritic hawaiite, seriate textured flow in CPL. The flow contains phenocryst of olivine and plagioclase in a groundmass of plagioclase, clinopyroxene, with minor amounts of Fe-Ti oxides and olivine. Plagioclase phenocrysts are complexly zoned and some have spongy cellular cores and olivine phenocrysts are often pseudomorphed by calcite.

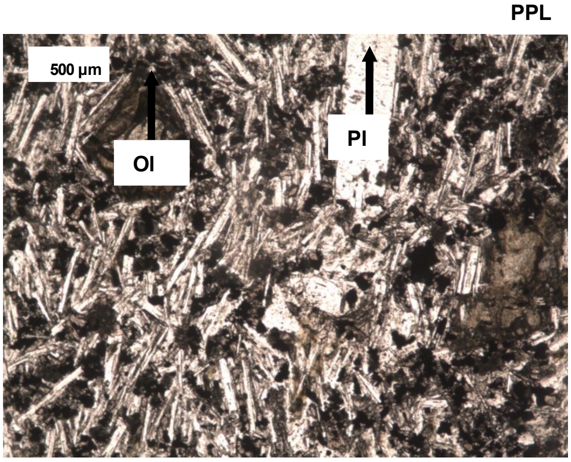


Figure 5.29b sample OPW-JG-06 Photomircrograph in PPL of a porphyritic hawaiite flow, plagioclase laths show flow textures.

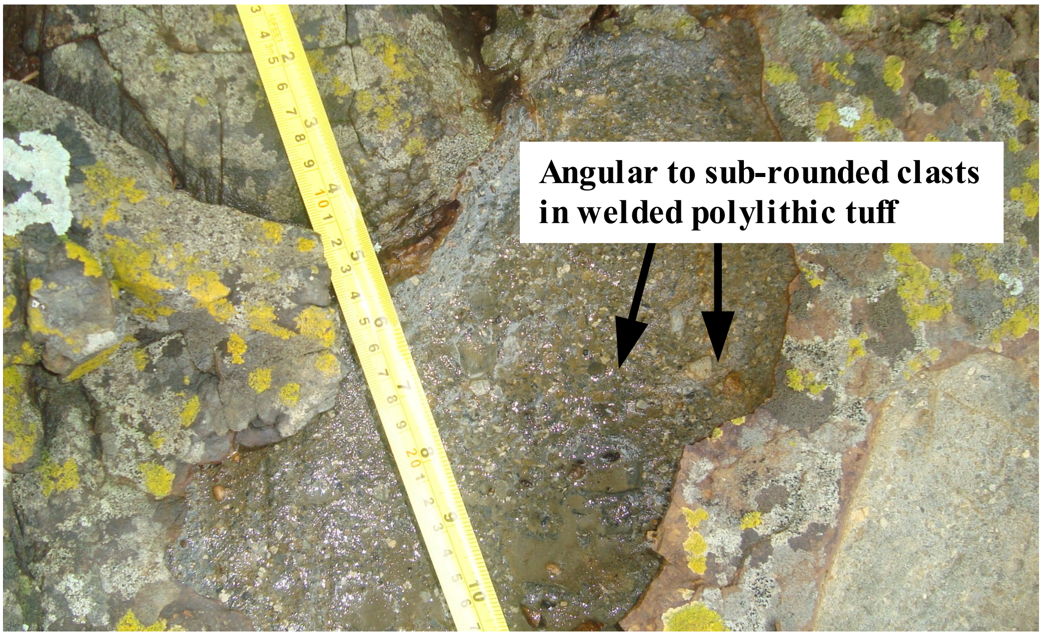


Figure 5.30a Field Photograph of the welded polylithic lapilli tuff on the west side of Onawe Peninsula showing the dark grey to black, poorly sorted, welded lapilli tuff with clasts range in size from < 1 mm to 15 mm.

Figure 5.30b Close up of welded polylithic lapilli tuff on the west side of Onawe Peninsula showing the variety of clast present.

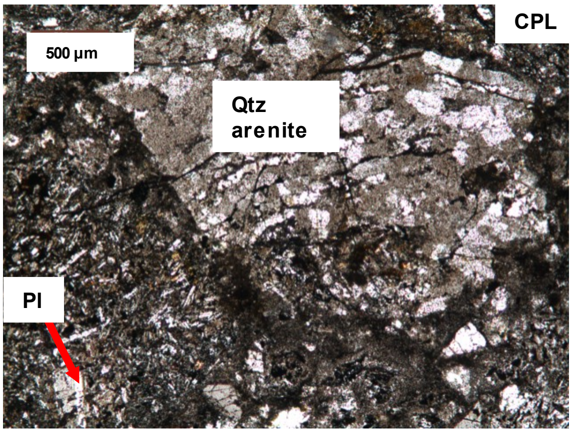


Figure 5.30c sample 3140. Photomicrograph of a welded polylithic tuff in CPL showing a large quartz arenite clasts and smaller angular clasts, and free plagioclase crystals welded together with minor amounts of basaltic glass.

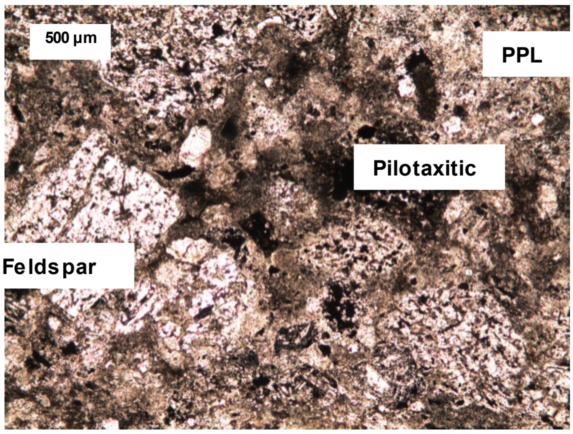


Figure 5.30d sample 3140. Photomicrograph of a welded polylithic tuff in PPL showing clasts of basaltic lavas and minor fragments of plagioclase, quartz arenite, and mudstone

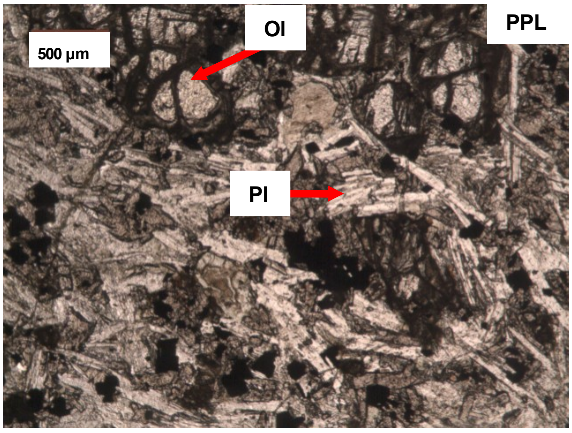


Figure 5.31a sample OPW-JG-12. Photomicrograph of a Picritic basalt lava flow in PPL which has both porphyritic and seriated texture. Phenocrysts consist of plagioclase and olivine in a groundmass of plagioclase, clinopyroxene, Fe-Ti oxides and olivine

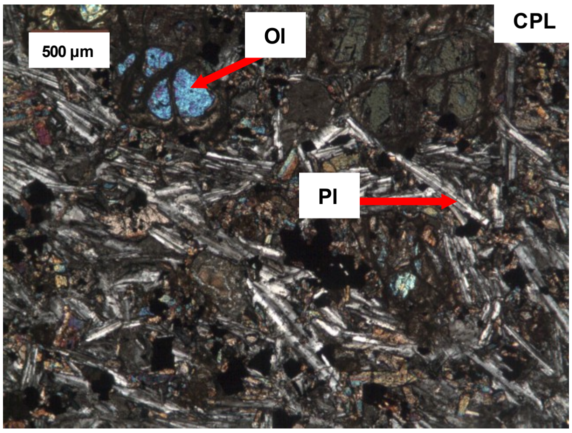


Figure 5.31b sample OPW-JG-12. Photomicrograph of a pictric basalt lava flow in CPL, showing flow aligned plagioclase laths.

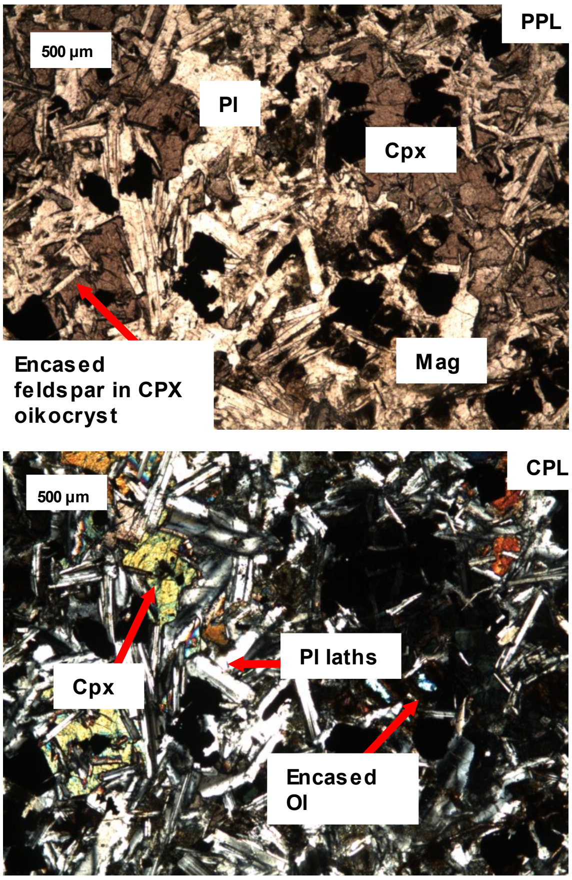


Figure 5.32 sample OPW-EH-01. **a) and b)** Photomicrographs of olivine alkali basalt with porphyritic and seriate-textures in PPL and CPL. Shown here are plagioclase, olivine and rare magnetite phenocrysts (< 10%) within a fine-grained, intergranular groundmass. Subophitic textures are present with, interstitial oikocrysts of clinopyroxene encasing plagioclase and olivine microcrystals.

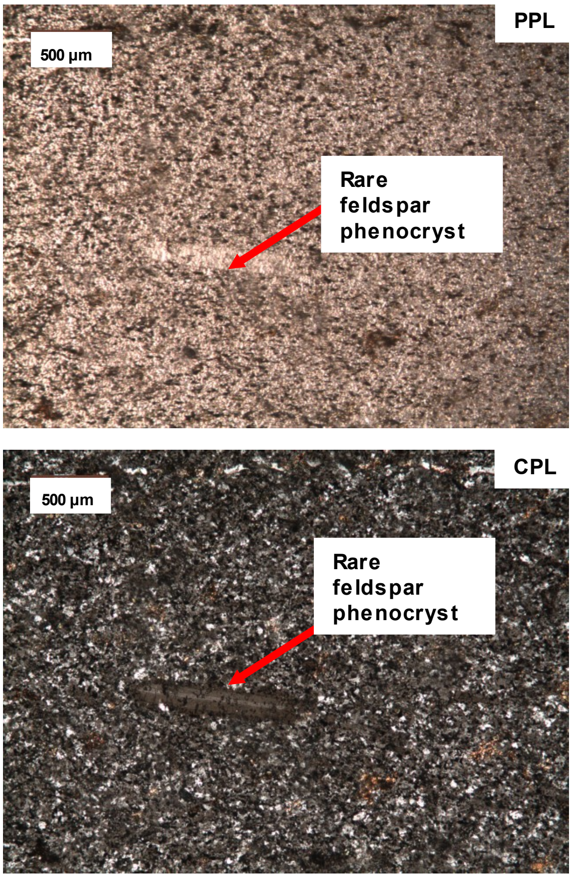


Figure 5.33 OPE-EH-01. **a)** and **b)** Photomicrographs of a mugearite flow in PPL and CPL. Flows are aphanatic, and only trace amounts of feldspar phenocrysts occur in a groundmass that is comprised of feldspar, clinopyroxene, Fe-Ti oxides, olivine and apatite.

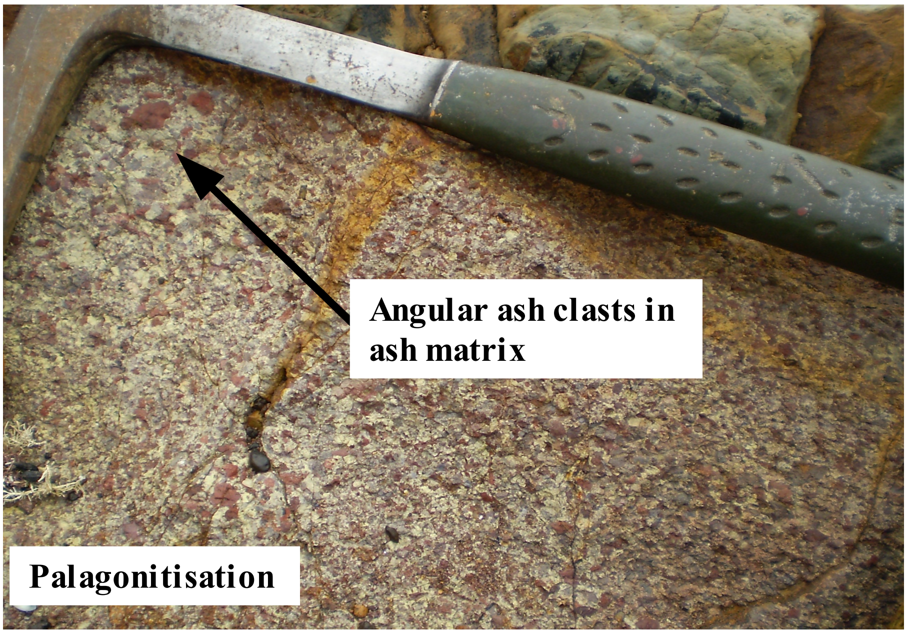


Figure 5.34a sample OPE-AT-01 Field photograph of an altered monomictic brecciated basaltic lapilli tuff, exposed on the shore platform of Northern Onawe Peninsula. The brecciated basaltic lapilli tuff consists of yellow - red brown lapilli tuff with accretionary lapilli. The deposit is highly altered and fractured with abundant palagonitisation and ragged 1 – 4 mm clasts in a fine ash matrix.

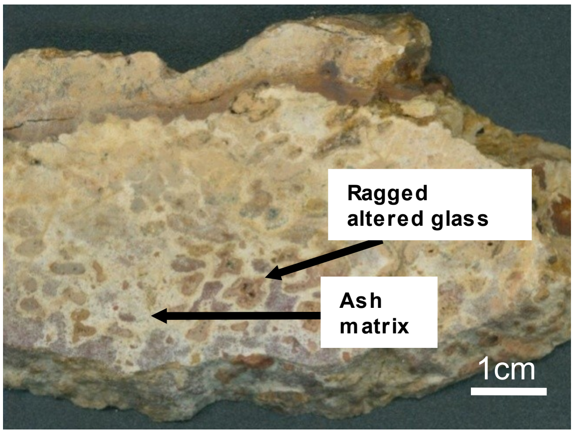


Figure 5.34b sample OPE-AT-01 Hand sample shows an altered monomictic brecciated basaltic lapilli tuff, with ragged 1 – 5mm glass clasts in a red to yellow ash matrix.

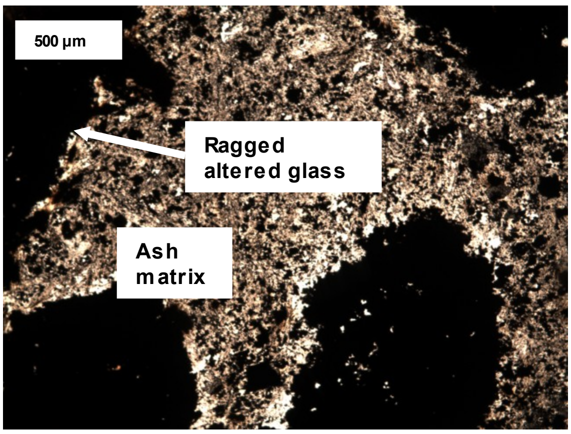


Figure 5.34c sample OPE-AT-01 Photomicrograph of a monomictic brecciated basaltic lapilli tuff comprised of fine ash (1/8 – 1/4 mm) with 1 -5mm altered ragged to blocky glass.

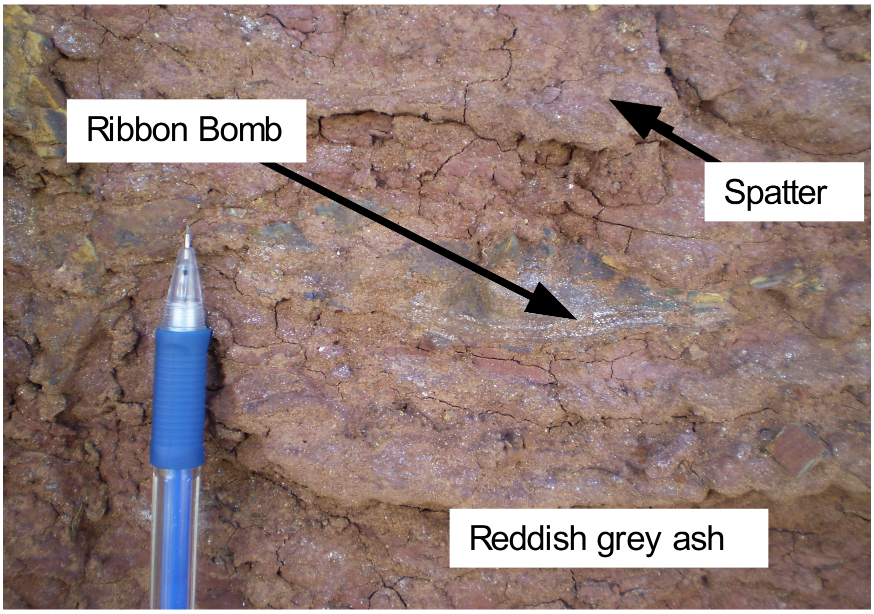
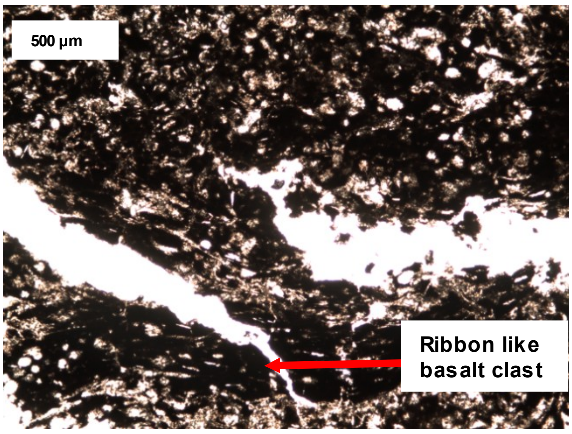


Figure 5.35a sample RB-AT-03 Field photograph of a spatter deposit from a scoria cone located at Robinsons Bay. The deposit consist of welded reddish grey, well bedded, fine to medium basaltic ash with elongate spatter and ribbon bombs.



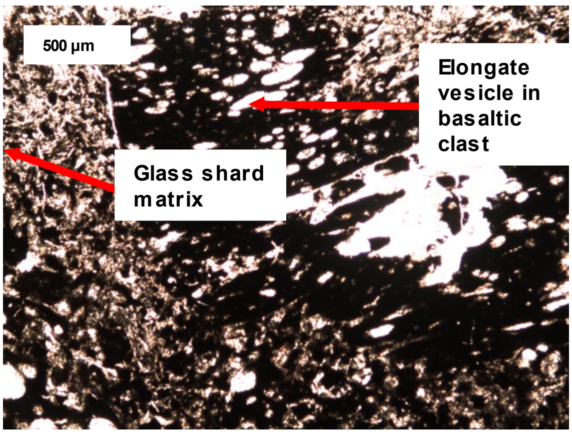


Figure 5.35 sample RB-AT-03 (Thin section 18) **b)** and **c)** Photomicrographs of spatter samples showing welded flattened vesicular basalt clasts in a glassy basaltic matrix.

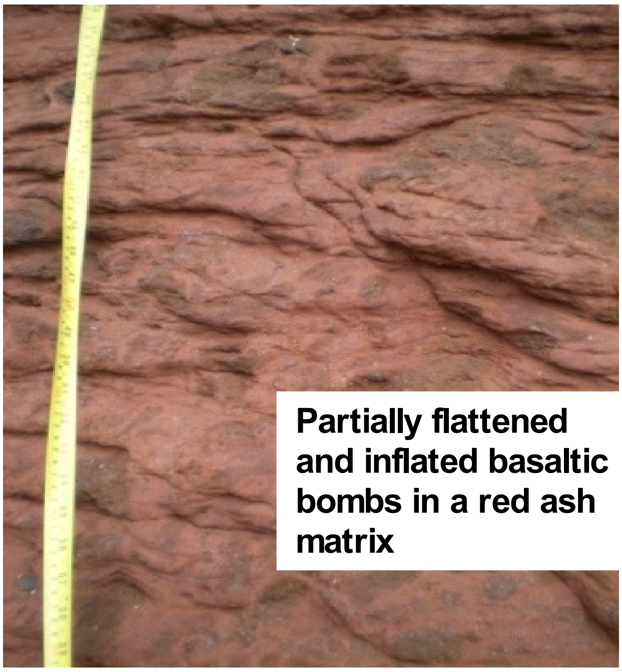


Figure 5.36a sample OPW-JG-09
Field photograph of a mixed scoriaceous deposits from a scoria cone located on the Northern end of Onawe Peninsula. The deposit consists of brownish red, well bedded, fine to medium basaltic ash with basaltic scoria and lava bombs . Bomb morphologies include ribbon spindle and cow dung bombs and range between large lapilli (5cm) and bomb size (30 cm).

Figure 5.36b sample OPW-JG-09
Cut section of a scoriaceous lapilli tuff with bombs

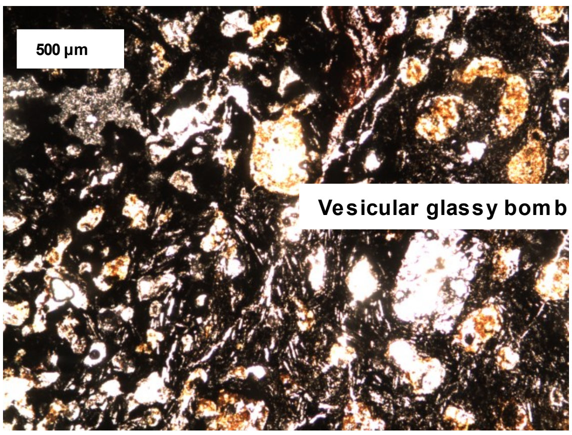


Figure 5.36c sample OPW-JG-09
Photomicrograph of scoriaceous lapilli tuff showing glassy vesicular bombs in a glassy ash sized shard matrix.

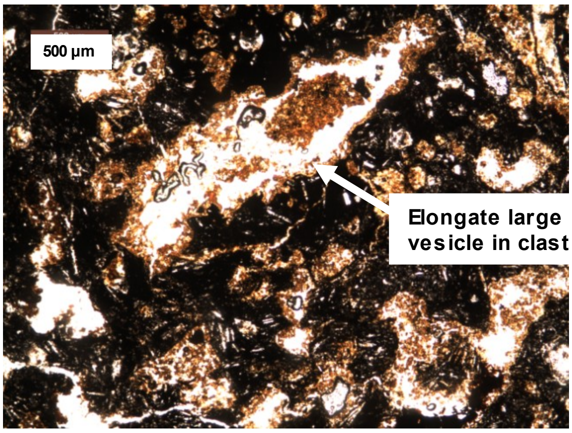


Figure 5.36d sample OPW-JG-09 Photomicrograph of scoriaceous lapilli tuff showing an elongate large vesicle in a basaltic bomb.

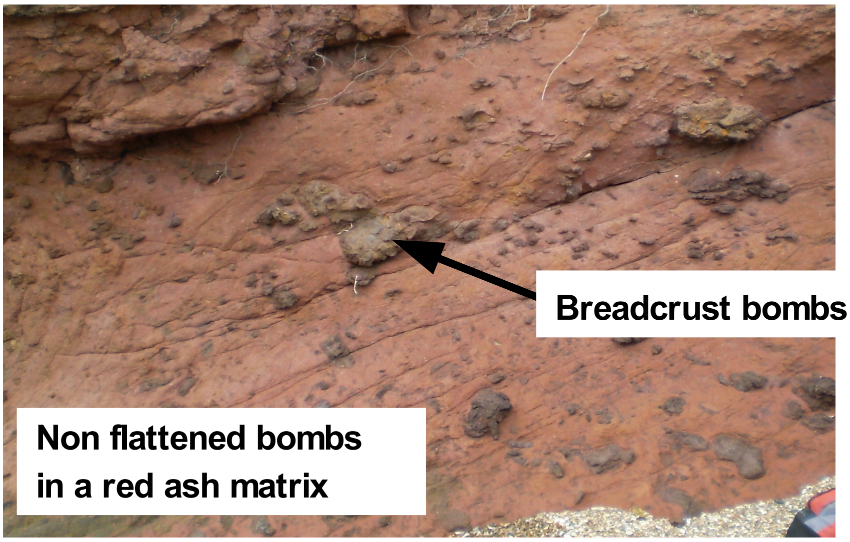


Figure 5.37 Field photograph of a non flattened scoriaceous deposit from a scoria cone located on Northern Onawe Peninsula. Deposits consist of brownish red, well bedded, fine to medium basaltic ash with basaltic scoria and lava bombs. Bomb morphologies are dominantly non flattened breadcrust and spindle bombs and range in size from small lapilli (~5 mm) to bomb size (<40cm).

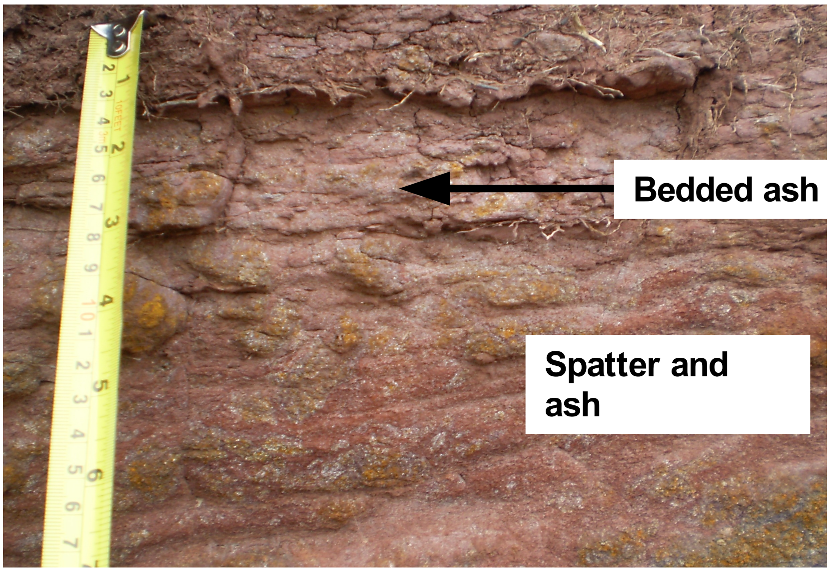


Figure 5.38 Field photograph of a ash rich deposit from a scoria cone on the Northern end of Onawe Peninsula. The deposit consists of brownish red, well bedded, fine to medium basaltic ash with well sorted lapilli spatter (~3 – 5cm). No thin sections of this layer were analysed as deposits were too weathered.

5.7 Mafic Stratigraphic sequences from different localities

The following section describes complete stratigraphic sections of different scoria cones located around the harbour. Refer to stratigraphic logs located in the appendix.

Northern Onawe Peninsula scoria cone (Stratigraphic log Fig 5.39 see appendix)

This stratigraphic sequence on the Northern Onawe Peninsula (Fig 5.2 see appendix) is a continuous sequence through a large scoria cone of the French Hill Formation (*af*). Due to the highly eroded nature of Akaroa Volcano in particular the inner shorelines of the Harbour, there is abundant outcrop exposure of the cone on both the eastern and western sides of Onawe Peninsula. This allowed detailed logs and measurements of the deposits to be obtained.

The sequence begins with a basal unit of brecciated basaltic lapilli tuff. This unit has a minimum thickness of 30 cm and is laterally extensive with much shore platform comprised of this deposit (Fig 5.2 see appendix). The deposit consists of highly altered, brecciated red ash with red, yellow and white 1 – 4 mm ragged lapilli clasts and occasional accretionary lapilli (Fig 5.34a)(Fig 5.34b)(Fig 5.39 see appendix).This deposit is highly altered and fractured with abundant palagonitisation. The brecciated basaltic lapilli tuff has a sharp upper contact (Fig 5.39 see appendix) with the next unit in the sequence, a welded spatter deposit. This unit consists of ~90cm of welded reddish grey, well bedded fine to medium basaltic ash with elongate spatter and ribbon bombs <15 cm in size (Fig 5.39 see appendix). This unit grades into ~80cm of brownish red, well bedded, fine to medium ash containing spatter, scoria and lava bombs (< 20cm)(Fig 5.39 see appendix). Bomb morphologies include flattened spatter, ribbon and cow dung bombs and non flattened breadcrust and spindle bombs. Another gradational contact marks the transition into a ~120cm deposit of brownish red, well bedded, fine to medium basaltic ash with scoria and lava bombs (Fig 5.39 see appendix). Bombs are predominately non flattened bread-crust and spindle bomb morphologies and reach sizes up to 30 cm in diameter. This unit grades into ~60cm of a deposit of welded reddish grey, well bedded fine to medium basaltic ash with elongate spatter and ribbon bombs with maximum clast size of 10 cm (Fig 5.39 see appendix).

Robinsons Bay Scoria cone (Stratigraphic log Fig 5.40 see appendix)

This stratigraphic sequence at Robinsons Bay (Fig 5.2 see appendix) is a continuous sequence through a large scoria cone of the French Hill Formation (*af*). The sequence begins with a basal unit of ~ 30 cm thick brecciated basaltic lapilli tuff. The deposit consists of highly altered, brecciated red ash with red, yellow and white 1 – 4 mm ragged lapilli clasts (Fig 5.40 see appendix). The brecciated basaltic lapilli tuff has a sharp upper contact with the next unit in the sequence. The next unit is an 80 cm thick scoria deposit, consisting of a well bedded (138/30NW) fine to medium ash containing abundant spatter (>5 mm) and moderate to large bombs (< 30 cm). Bombs morphologies are predominantly flattened and include elongate spatter, ribbon, spindle and cow pat bombs (Fig 5.40 see appendix). This unit grades into 90cm of bedded spatter dominated tuff with small - medium bombs (<10cm). Bomb morphologies are predominantly rounded - oval and display show NW orientations (Fig 5.40 see appendix). This unit grades into a thin (20 cm) deposit of lapilli and small bombs (7 cm) in an ash rich layer (Fig 5.40 see appendix). The most discernible differences from the previous unit is the low abundance of spatter and the vast reduction in bomb size. An irregular gradational contact marks the transition into a 1.4 m scoriaceous deposit comprised of medium cow pat bombs (8 cm by 15 cm), large ribbon bombs (180 cm by 40 cm) and elongated ribbon bombs in an ash and spatter matrix (Fig 5.40 see appendix). A sharp gradational contact precedes a 80 cm welded reddish grey, well bedded fine to medium basaltic ash with elongate spatter and ribbon bombs (Fig 5.40 see appendix). This unit is topped by a vegetated slump and therefore it is unclear if a complete sequence is preserved.

5.8 Plutonic Rocks

The Duvauchelle Gabbro *(ad)* and Onawe Syenite *(ao)* are the only plutonic rocks exposed on Akaroa volcano. The two deposits occur on the southern tip of Onawe Peninsula, and are the younger plutonic equivalents to the volcanic rocks of the Akaroa Volcanic Group (Fig 5.2 see appendix). The syenite forms a massive convex intrusion as a result of spheroidal weathering. In contrast the gabbro occurs as two narrow outcrops (5 – 10m) occurring to the north of the syenite on both the Eastern and Western sides of Onawe Peninsula. On the West side of Onawe Peninsula the contact is defined by a 1.2 metre wide trachyte dyke (Fig 4.4), while on the eastern side the contact is not observed. Although the relationship between the plutonic rocks is not directly observed, the syenite appears to be the younger of the two intrusions based on Ar-40/Ar-39 dating (Timm et al. 2009) and field observations. The syenite is intruded by a relatively small number of dykes compared to the surrounding volcanic deposits, suggesting a later period of emplacement.

Duvauchelle Gabbro (ad)

The Duvauchelle Gabbro (*ad*) consist two small outcrops of massive, dark grey to black, biotite - olivine gabbro. On the eastern Onawe Peninsula the gabbro contains lensoidal pockets (< 10cm) of more felsic material, which range from a monzodiorite to monzonite (Fig 5.41).

Thin section

The Duvauchelleee Gabbro consists of a phaneritic equigranular intrusion. Crystals are 1 – 5mm in size and consist of plagioclase, clinopyroxene, Fe-Ti Oxides, olivine, biotite and minor amounts of amphibole, alkali feldspar, quartz and apatite (Fig 5.42). Olivine is typically anhedral, with well developed fractures that are often altered to red-brown iddingsite (Fig 5.42). Plagioclase is the most abundant mineral, dominantly occurring as euhedral multi zoned crystals; however, a few equant crystals of plagioclase and olivine are enclosed within clinopyroxene forming a poikilitic texture (Fig 5.42). Iron oxides and quartz are interstitial in nature and biotite and amphibole are subhedral in shape (Fig 5.42). In altered samples clinopyroxene and olivine are often pseudomorphed to calcite and amphibole is altered to allanite (Fig 5.42). Within the gabbro miarolitic cavities and felsic pockets occur. Crystals are < 2cm in size and consist of zoned plagioclase and alkali feldspar with quartz (Fig 5.42). Rare apatite inclusions also occur.

Onawe Syenite (ao)

The Onawe Syenite consists of a massive spheroidal pluton on the southernmost tip of Onawe Peninsula (Fig 4.4). The deposit consists of a creamy yellow, massive, coarse grained, spheroidally weathered syenite (Fig 4.4), which contains irregular drusy cavities that are often infilled with quartz.

Thin section

The Onawe Syenite is a coarse grained (2-5mm) phaneritic, equigranular rock that predominantly consists of microperthitic alkali feldspars, plagioclase and minor amounts (< 10 %) of quartz, spinel, clinopyroxene and fayalite (Fig 5.43a). Alkali feldspar is commonly altered to sericite and fayalite and clinopyroxene crystals are partly or completely replaced by calcite pseudomorphs (Fig 5.43b). Voids are often infilled by quartz and minor calcite.

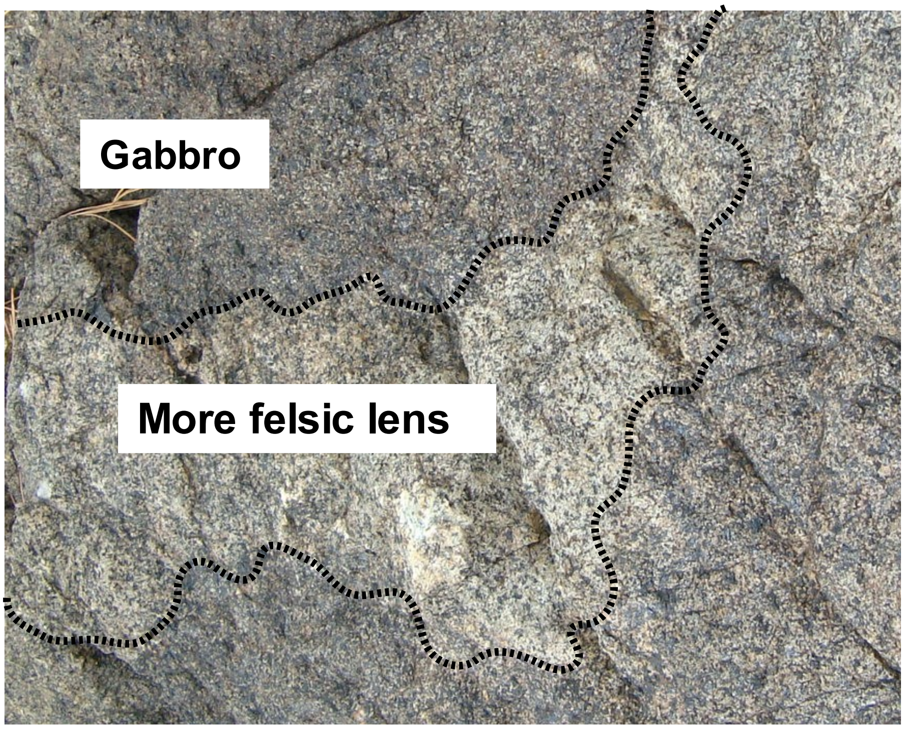


Fig 5.41 Field photograph of Duvauchelle Gabbro (*ad*) outcrop exposed on Onawe Peninsula. The outcrop consists of dark grey to black, biotite - olivine gabbro with lensoidal pockets of more felsic material.

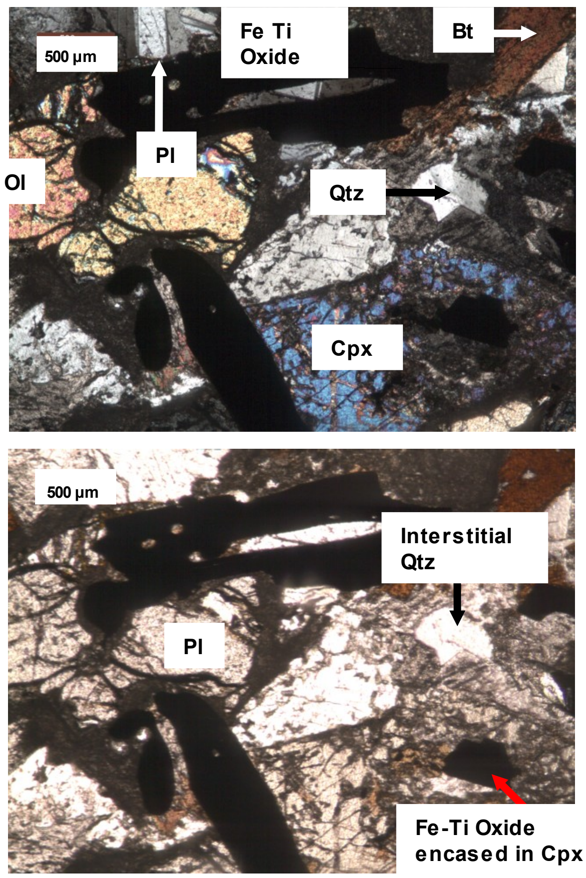


Figure 5.42 sample OPW-EH-03 Photomicrographs in CPL and PPL showing a phanaritic gabbro comprised of interlocking clinopyroxene, plagioclase, olivine, biotite, Fe Ti Oxides and quartz. Olivine alteres to iddingsite along fractures and clinopyroxene is poikilitic encases plagioclase and olivine crystals.

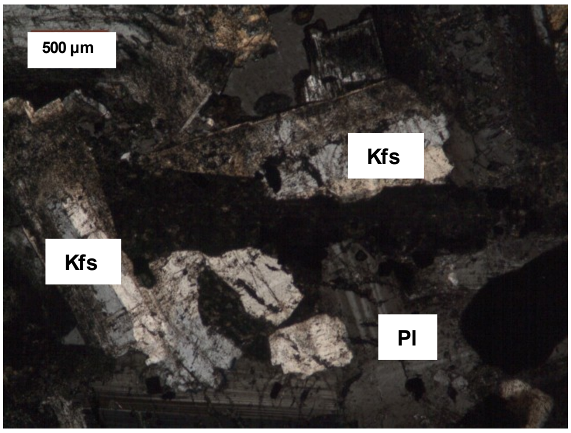


Figure 5.43a sample OPE-JG-12 Photomicrograph in CPL of a phanaritic syenite comprised of alkali feldspar, plagioclase and Fe – Ti Oxides. Alkali feldspar is often shows well developed sericite alteration.

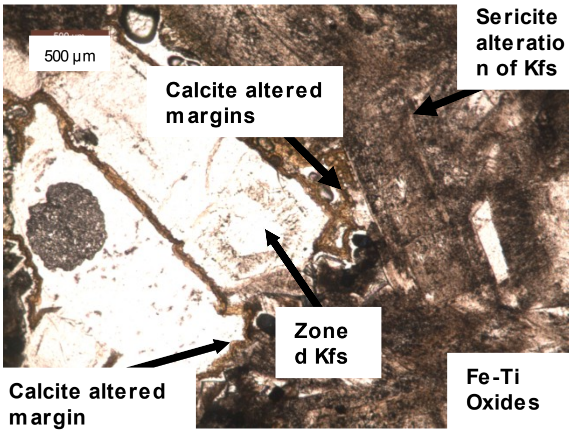


Figure 5.43b sample OPE-JG-12 Photomicrograph in PPL of a phanaritic syenite comprised of alkali feldspar, plagioclase and Fe – Ti Oxides. Alkali feldspar is often shows well developed sericite alteration.

6. Discussion

6.1 Lithofacies associations / assemblages

The study of volcanic facies involves the identification and documentation of distinct characteristics of rock units to determine origins, depositional process and depositional environments (Cas and Wright 1987). Volcanic facies are commonly divided into proximal, medial and distal facies as transport and depositional mechanism often change 'en route' (Németh and Martin 2007).

Lithofacies are distinguishable mapped rock units that are defined by structure, texture, internal organisation, geometry and lithological components. Vertical and lateral variations in lithofacies allow changes in depositional behaviour of the unit to be identified (Németh and Martin 2007). To reconstruct a volcano's eruptive history and volcanic processes lithofacies are often put into lithofacies associations, which are collection of facies that occur together and are related to the same source (Cas and Wright 1987).

The main facies associations that are common in emergent composite shield volcanoes include scoria cones (Fig 6.1), subaerial lava domes (Fig 6.2), subaqueous lava domes (Fig 6.3), tuff cones (Fig 6.4) and tuff rings.

Scoria Cones

Scoria cones consist of crater (CF), upper crater (UCF), wall (WF) and talus slope facies (TSF) (Fig 6.1) (Vesperman and Schmincke 2000) The crater facies (Fig 6.1) can be divided into a lower and mid crater facies. The lower crater facies is typically comprised of Hawaiian-style deposits that consist of densely welded spatter (Fig 6.1) as lava is still molten as it lands. The mid crater facies (Fig 6.1) consists of transitional deposits that are partially welded (Fig 6.1); however individual clasts are able to be discerned.

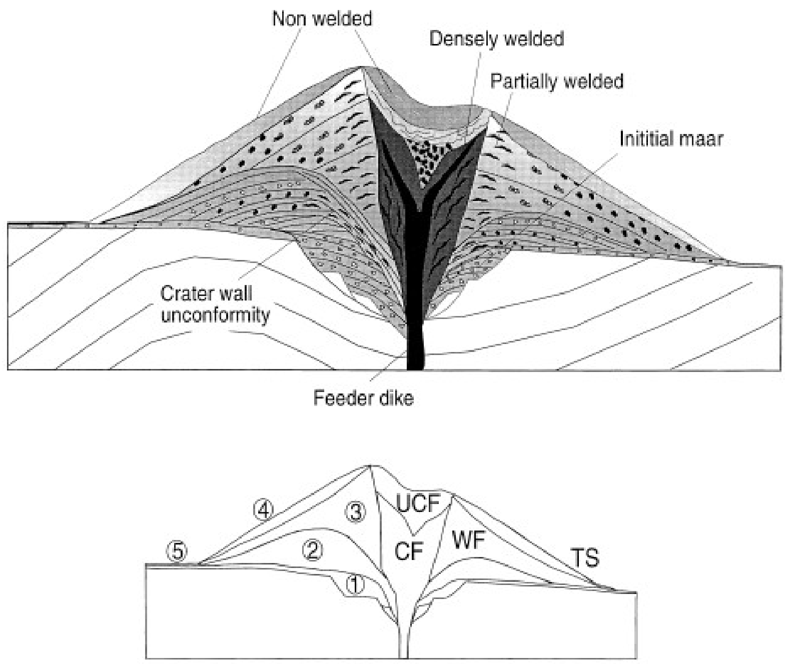


Figure 6.1 Scoria cone structure and facies associations (after Vesperman and Schmincke 2000) 1 - Initial phreatomagmatic deposits, 2 - Strombolian deposits with intercalculated phreatomagmatic beds, 3 - Cone forming strombolian deposits, 4 - post strombolian talus, 5 - distal fallout tephra, CF = crater facies, UCF = upper crater facies, WF = wall facies, TS = talus slope.

The upper crater facies (Fig 6.1) consist of strombolian non welded deposits consisting of rounded bombs in a poorly sorted lapilli matrix (Fig 6.1). This unit is often overlain with thick layers of well-sorted lapilli; this lapilli layer is often seen great distances from the cone itself.

The outer wall facies (Fig 6.1) frequently has a brecciated basal fine ash with accretionary lapilli, which is often overlain with a coarse grained poorly sorted breccia rich in accidental lithics (Fig 6.1). These deposits represent the initial phreatomagmatic stage of the volcano’s activity.

The inner wall facies is characterised by bedded, coarse grained, scoria bombs and lapilli proximal to the vent, and deposits are moderately welded and become increasingly less welded, uncompacted, and finer grained in the distal facies (Fig 6.1).

The outer flanks of many scoria cones are covered by fall layers of well sorted lapilli (Fig 6.1) and subsequent degradation of these deposits results in one further facies association; the talus slope facies.

Subaerial Lava dome facies

Silicic subaerial lava domes typically consist of thick (tens to hundreds of m), small diameter (< a few km), small volume domes due to their high viscosity (McPhie et al. 1993). Domes typically consist of solid lava, autobreccia layers or carapace, talus apron and sometimes block and ash flow deposit facies associations (Fig 6.2a)(Fig 6.2b).

Dome interiors consist of sold lava and have various textures depending on the composition, rheology and crystallisation history. Typically domes deposits consist of porphyritic to aphyric lavas with a crystallised centre surrounded by spherulitic obsidian, obsidian, finely vesicular pumiceous lava and an autoclastic carapace breccia (Fig 6.2a)(Fig 6.2b) (McPhie et al. 1993).

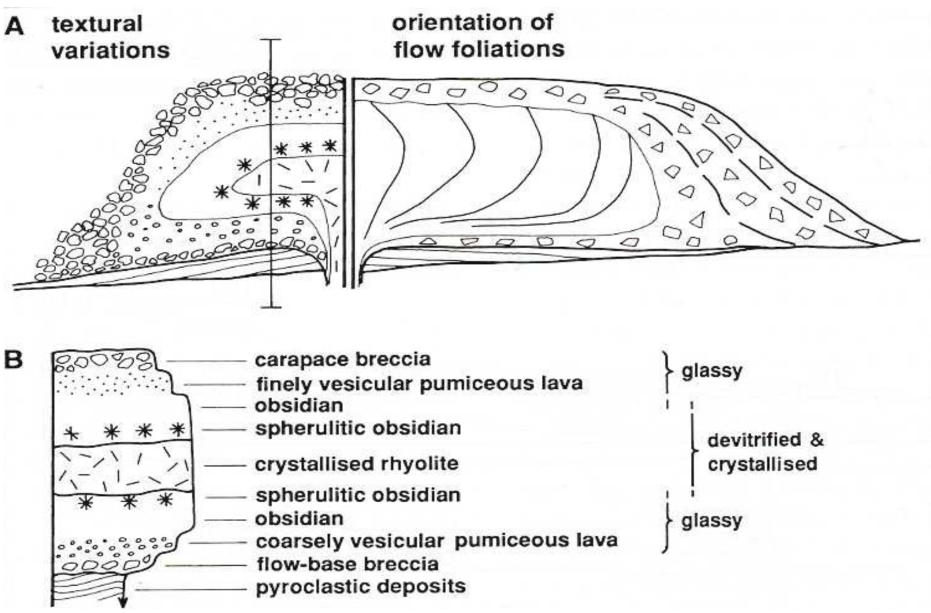


Figure 6.2 a) Schematic cross section through a sub-aerial silicic lava dome. Showing common textural variations resulting from vesiculation, devitirification and flow fragmentation. The right side shows flow foliations and layering of the talus breccia. **b)** Vertical section displaying textural zones. Modified from Fink and Manley 1987 and Duffield and Dalrymple 1990 after McPhie et al. 1993.

Carapace breccias are a result of a flowing dome interior causing fragmentation of the dome margins creating an autobrecciated zone on the basal, upper and side contacts. This auto-brecciated facies consists of a brecciated dome carapace comprised of a breccia of blocky, slabby or irregular lava blocks in a granular matrix (Fig 6.2a)(Fig 6.2b). The deposits are monomictic, clasts supported, matrix poor, poorly sorted and flow banded and pumiceous clasts are common (Mcphie et al. 1993). Although the breccia may appear to have random clast sizes, the average block sizes generally decrease outward systematically from the vent area (Fink and Anderson 2000).

Silicic domes are often associated with deposits resulting from gravitational collapse. These products include aprons of talus breccia that accumulate at the dome margins during and after emplacement of the dome, and more dispersed block and ash flow deposits resulting from partial collapse of over steepened domes.

Aprons of talus breccia are an accumulation of rock fragments at the bases of cliffs which are normally associated with steep flow fronts of domes (McPhie et al. 1993). Talus breccias are clast supported, matrix poor, massive or weakly stratified, and clasts are monomictic. However a large range of textures can occur as the clasts are derived from different parts of the parent dome (McPhie et al. 1993). Transport is typically minimal so clasts are often bounded by original fracture surfaces, although abrasion may alter clast edges and produce some rounding.

When lava domes over-steepen, partial collapse of domes can occur, resulting in block in ash flows. Block and ash flows can therefore represent medial to distal facies associated with lava domes. Block and Ash flows may be triggered by both gravitational collapse of a lava dome, or through shock-induced collapse as a result of vulcanian eruptions. Deposits are often described as monolithic; however a large range of textures may be observed, and it is often difficult to distinguish between juvenile material and older dome fragments because of the intrinsic large variation in dome textures.

Typically deposits contain little fine ash (<1/16 mm, usually less than 5 wt %) and have a large proportion of dense to moderately vesicular pumiceous blocks up to several metres in diameter that are derived from the juvenile source dome (Freundt et al. 2000). Clasts include intact lapilli and blocks of vesicular pumice, glassy shards (pumice fragments) and free crystals. Block and ash flow deposits contain less vesicular clasts than other types of pyroclastic clasts and pyroclastic density current deposits, and are generally smaller in volume (typically 1 – 10m thick and thinning to 1 – 2 m at their lobate ends) (Freundt et al. 2000). The deposits are poorly sorted, while bedding can be clast or matrix supported and is generally massive, although faint layering may occur. The blocks are either uniformly distributed through the bed or sometimes show normal or reverse tail grading.

Shallow subaqueous lava Domes

Shallow subaqueous lava domes are often obscured from the rock record. Therefore, to determine eruptive centres and processes it is crucial to observe facies associations. Shallow subaqueous lava domes are typically associated with effusive, phreatomagmatic, and magmatic explosive behaviour, and are also often associated with mass flow resedimentation and reworking of volcaniclastic deposits (McPhie et al. 1993). Lithofacies typically consist of proximal coherent dome facies, followed by autobreccias, hyaloclastites, redeposited breccias (Fig 6.3), and if sustained eruptive deposition occurs, subaerial tuff cone related facies (see tuff cone section).

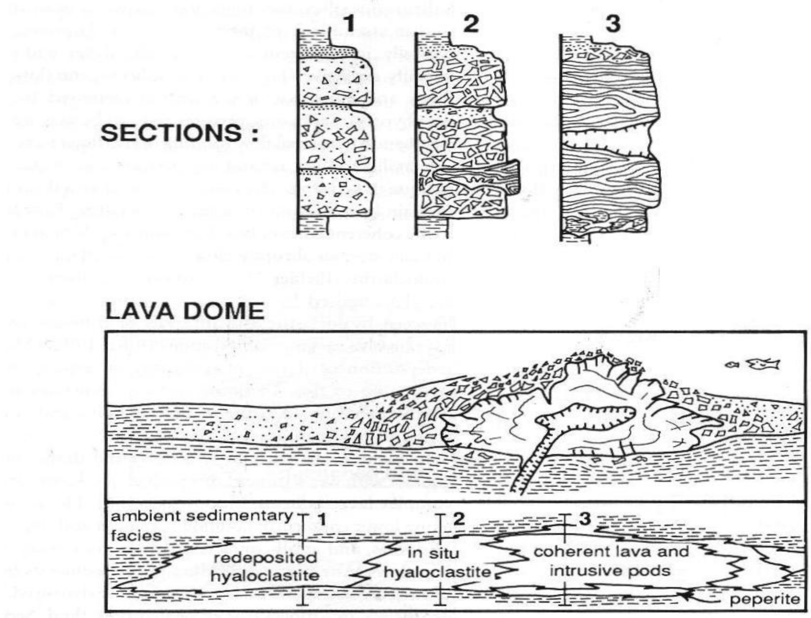


Figure 6.3 Character and distribution of contemporaneous volcanic facies, that develop in association with the emplacement of submarine domes (after McPhie et al. 1993). (1), (2), (3), mark the localities of the graphic logs in the top diagram. Each section samples genetically related facies that differ in character, texture and internal organisation. Coherent lava in one section may be the direct correlate of bedded volcaniclastic breccia in an adjacent section

The coherent dome facies and autobreccias' internal structures are similar to subaerial domes (Németh and Martin 2007). However the most obvious physical difference between subaerial and subaqueous emplacement of silicic lavas is the abundance of quench textures.

Quenching of melt results in the formation of large proportions of quench fragmented lava clasts known as hyaloclastites (Németh and Martin 2007). Hyaloclastites form from non-explosive fracturing and disintegration of quench lavas. This can occur as a consequence of (a) subaerially erupted lava flows into water, (b) lava erupted subaqueously, (c) magma intruded into wet sediment, water or fluid filled cracks and (d) pyroclasts erupted into or deposited on water.

Hyaloclastites typically consist of unstratified monomictic clasts ranging in size from < 1mm to 10's of centimetres that show jigsaw fit textures as clasts fragment in situ (Fig 6.3) (Fig 6.4) (McPhie et al. 1993). Some in situ hyaloclastites display a clast within matrix texture due to varying degrees of fragmentation, with the matrix consisting of more fragmented fine hyaloclastite surrounding less fragmented areas. In situ hyaloclastites may occur as thin margins or as thick deposits that completely mask the coherent lava facies of the dome (Fig 6.4)(e.g. Scutter et al. 1998; DeRita et al. 2001).

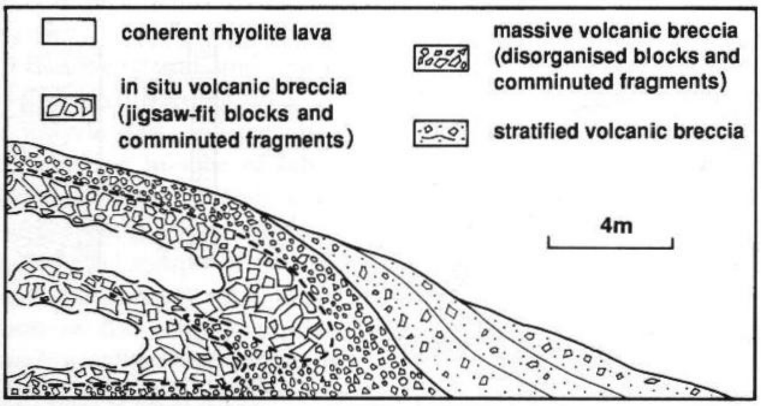


Figure 6.4 Schematic volcanic facies associated with subaqueous emplacement of rhyolite lavas; Miocene, Ushikiri Formation, Japan. (After Mcphie et al. 1993 modified from Kano et al. 1991)

In subaqueous settings resedimentation of the hyaloclastite breccia is common, and mass flow redeposited hyaloclastites commonly show evidence of transportation such as bedding, mixing of clast textures and an absence of jigsaw fit textures (Fig 6.3) (Fig 6.4)(Cas et al. 1990).

Tuff Cones and Tuff Rings (volcanic successions)

Tuff cones and rings are among the most common volcanic land forms (Cas and Wright 1987; Vespermann and Schmincke 2000). They are formed when ascending magma interacts explosively with surface water (tuff cone) or ground water (tuff ring). This proximity to standing water makes tuff cones vulnerable to rapid erosion; however, this is frequently advantageous for geological study as large portions of the inner sections can become accessible to study (Cole et al. 2001; Sohn and Park 2005; Németh and Cronin 2006).

Tuff cone morphologies differ from tuff rings, having smaller craters and larger height to width ratios. They are formed in areas where surface water is located above the vent, and cones typically have bedding angles between >20-25° near rim crests. In contrast, tuff rings typically have bedding angles < 25° (Cas and Wright 1987) (Fig 6.5).

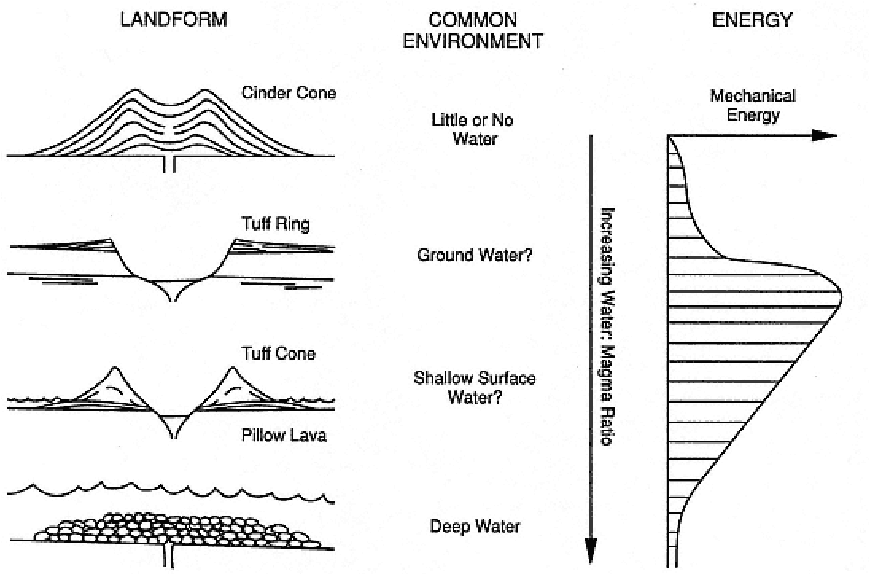


Figure 6.5 Comparative diagram between magma to water ratio mechanical energy and the resulting volcanic landforms using pure coolant (water) as an interactive media with magma. After White 1996.

Tuff cone deposits result from low energy surge and fall eruptions and their primary facies consist of an initial basal volcanic breccia, followed by thinly bedded lapilli tuff, and then a main cone forming weakly bedded tuff or lapilli tuff. The basal volcanic breccia typically represents an initial phreatic vent clearing stage, and usually contains angular fragments of country rock deposited predominantly by ballistic fallout. This is often interbedded with less coarse fall deposits and finer grained surge deposits (Cas and Wright 1987). The dominant tuff cone-forming process is low density pyroclastic density currents (pyroclastic surges) and minor higher density pyroclastic density current (pyroclastic flow) components. These deposits consist of thinly bedded lapilli tuff deposited by inflated surge deposits with minor air fall and weakly bedded lapilli tuff or tuff, deposited by poorly inflated surges and falls. Lateral facies variation in tuff cones differ from tuff rings, deposits are less extensive because of the higher wetness of the eruption cloud. These wetter and therefore denser surges do not propagate far from the vent depositing accreationary lapilli in crudely stratified deposits (Verspermann and Schmincke 2000).

Tuff rings are the product of high energy surge eruptions in which clouds of pyroclastics are transported large distance from the vent. Tuff ring morphologies differ from tuff cones as their diameters range from a few hundred m to 3 km, and crater rims are generally less than 50 m higher than surrounding land. They have relatively steep rims which dip both inwards and outwards and typically beds dip at <25˚ (Verspermann and Schmincke 2000). Facies usually consist of a basal volcanic breccia and thinly bedded lapilli tuff and tuff deposits resulting from surges with minor air fall. Deposits show distinct lateral facies changes and therefore can be divided into proximal, medial and distal facies.

Lateral facies variations have been recognised from, among others at the crater of Elegante Volcano in Sonora Mexico (Wohletz and Sheridan 1979). Proximal facies consist of sandwave bed facies replaced by massive facies in the medial regions and planar bed facies in distal regions (Fig 6.6) (Table 6.1) (Wohletz and Sheridan 1979). However facies analyses of pyroclastic surge deposits associated with tuff rings on Cheju Island, Korea recognised a different trend. Sohn and Chough (1989) found proximal deposits to be relatively unbedded, massive and disorganised in nature (Fig 6.7). Medial facies were composed of massive units grading to sandwave bedded units. Distal areas were planar or sandwave deposits, that consisted of thinly bedded and laminated tuffs in the most distal areas (Fig 6.7). These lateral facies changes were attributed to high particle concentrated turbulent flows near the vent resulting in a rapid loss of suspended material and therefore limiting tractional processes that form bedding structures. As the particle concentration decreased with distance from the source, tractional processes became more dominant resulting in the development of bedding structures.

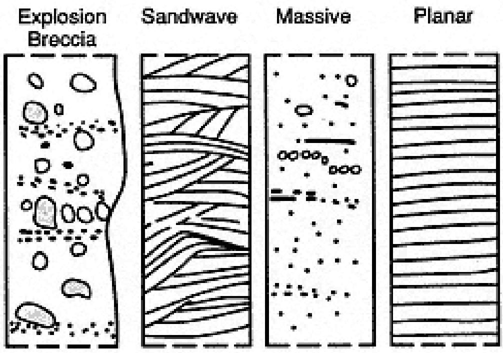


Figure 6.6 Recognised lateral facies transitions from the tuff cones of Sonora, Mexico. From Wohletz and Sheridan 1983.

Facies	***Characteristics***
Vent	Explosion breccia, consisting of large blocks and bombs that are both framework and matrix supported; matrix of coarse ash, intercalations of fallout lapilli, and surge beds
Sandwave	Predominantly sandwave to massive bedding transitions; low primary dips; little alteration; fine grain sizes
Massive	Sandwave, massive, and planar bedding structures all present—massive beds predominating and showing some alteration, up to 25° dips near vent
Planar	Planar beds predominate, some massive beds; coarse grain sizes; may have high primary dips near vent
Wet Surge	Strong evidence of wet emplacement, including abundant accretionary lapilli; high primary dips with soft-sediment deformations; poorly developed stratification; palagonitization; induration; tuff-breccia appearance; intergranular vesiculation; bedding consists mostly of massive, planar, and laharic textures
Dry Surge	Fresh deposits poorly indurated with little palagonitization; thinly bedded, sandwave facies change to massive then to planar facies with increasing distance from vent beds; low primary dips
Tuff Cone	Explosion breccia near vent at base; overlain by small amounts of dry surge and abundant wet surge deposits and lahars
Tuff Ring	Mostly dry surge deposits overlying explosion breccia and fallout beds near vent
Composite Cone	Alternating dry and wet facies; dry surges show progression from planar to massive to sandwave facies with increasing distance from vent; wet surges change to lahars with distance from vent
Caldera	Dry surges at base above Plinian fallout, becoming wetter as eruption progresses and pyroclastic flows are deposited; pyroclastic flows can be surge-like in caldera eruptions that are hydrovolcanic

Table 6.1 Descriptions of recognised facies from the tuff cones of Sonora, Mexico. From Heiken and Wohletz 1983

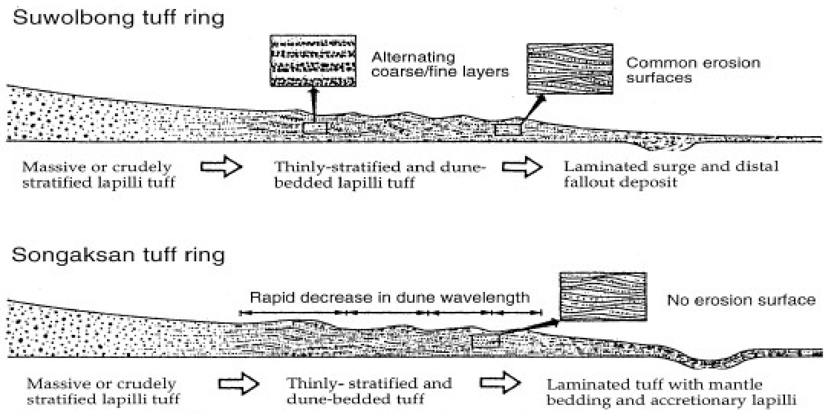


Figure 6.7 Lateral facies variations of base surges, Cheju Island Korea. In the Suwolbong tuff ring. Proximal lapilli tuffs are crudely stratified or massive with inversely graded bases. In medial parts, thinly stratified beds or dune-bedded lapilli tuff dominate. Segregation of coarse and fine grains into distinct layers reveals cohesion-less transport. In distal sections, thinly stratified and wavy-bedded tuffs are present. The Songaksan tuff deposits show similar facies variations, although accreationary lapilli, plastering of deposits on vertical obstacles and absence of erosional structures suggest wetter surges (Adapted from Sohn 1996)

6.2 Interpretation of the trachytic facies

We propose the trachytic facies observed around Akaroa harbour represent the proximal and medial facies of tuff rings and a lava dome/coulee/flow that interacted with seawater.

The massive monomicitic trachyte tuff breccia (Lushington Breccia Formation *al)*, best observed at Lushington Bay and seen at Onawe Peninsula, French Farm Bay and on a road cut between French Farm Bay and Barrys Bay is interpreted as representing a proximal hyalolastite carapace of an emergent to shallow subaqueous lava dome/coulee/flow (Table 6.2 see appendix)(Fig 6.3)(Fig 6.4). The deposit is a clast supported, monomictic, massive to poorly bedded (Fig 5.4) tuff breccia with jigsaw fit textures (Fig 5.5) and a minimal ash shard matrix (Fig 5.14a) (Fig 5.14b). This suggests in situ fragmentation concordant with a coulee or dome carapace breccia (McPhie et al. 1993).

A diverse range of clast textures are observed, (Fig 5.14a)(Fig 5.14b) both non vesicular and pumiceous in style. Pumiceous, flow banded, dense recrystallised (sericite recrystallisation), perlitic, spherulitic, quenched and smaller glassy clasts are present (Fig 5.14b). The pumiceous, flow banded and spherulitic clast types are consistent with that of a brecciated dome carapace (McPhie et al. 1993). However, the quenched textures (Fig 5.14b), extensive recrystallisation (Fig 5.14b), perlitic textures, and smaller glassy blocky clasts are more consistent with a hyaloclastite or possibly hydroclastite deposit. Therefore this unit likely represents a hyaloclastite carapace of a lava dome/coulee/flow, as has also been described for similar sequences elsewhere (e.g. De Rosen-Spence et al. (1980). The proximity to the paleo sea level (slightly higher than present day sea level) (Martin 2000) suggests external standing water provided the primary water source rather than groundwater (Wohletz and Sheridan 1983; Sohn 1996).

The thickness and spatial distribution of the deposit within the harbour (Fig 5.2 see appendix) constrains the morphology and extent of the hyaloclastite dome and its associated flow carapace, which formed from explosive shattering of lava. The deposit reaches its maximum thickness (>12.5m) between Lushington and Takamatua Bays (Fig 5.4) and thins towards Petit Carenage Bay (~2.2m) French Farm Bay (~2.2m) and Onawe Peninsula (~ 1.1m). The spatial distribution of the deposit (6 km^2) and thickness suggests a flow/coulee rather than a lava dome. However submarine silicic flows are commonly dome shaped or tabular in form and therefore it is slightly semantic to distinguish between domes and flows.

The monomictic trachytic lapilli tuff, best exposed at Onawe Peninsula (Fig 5.2 see appendix)(Fig 5.6a)(Fig 5.6b)(Fig 5.6c)(Fig 5.20 see appendix), is part of the Lushington Breccia Formation (*al*). This unit is interpreted as representing a proximal to medial surge deposits from an emergent subaerial tuff ring that formed on the earlier trachytic hyaloclastite coulee discussed above (Table 6.2 see appendix)(Fig 6.3)(Fig 6.4).

The trachytic lapilli tuff consists of dense trachyte clasts with a minor amount of pumiceous clasts (Fig 5.15a). However this deposit was most likely dominated by pumiceous juvenile trachyte. As dense clasts have recrystallised to sericite (Fig 5.15b) a product of extensive alteration. The juvenile nature of some clasts and extensive alteration of others suggests a phreatomagmatic eruption style.

The deposit initially begins with a bedded, matrix to clast supported, moderate to well sorted, disorganised to normally graded (Fig 5.6a)(Fig 5.6c), section (Fig 5.20 see appendix). This section is comparable to the tuff cones on Cheju Island, Korea (Sohn and Chough 1989) and most likely represents the proximal facies of a tuff cone with relatively disorganised beds (Table 6.2 see appendix). The normal grading of individual beds in the deposits (Fig 5.6c) suggest minor pulsating eruptions or possible minor gravitational sorting during settling in a shallow non turbulent sea. The disorganised thicker beds represent pyroclastic surge deposits. The next section is composed of a massive trachytic lapilli tuff (Fig 5.20 see appendix). This change in the deposit most likely represents the change in facies from proximal to medial (Table 6.2 see appendix) as both the deposits and transitions are comparable to those of Cheju Island, Korea (Sohn and Chough 1989).

The thickness and spatial distribution of the deposit within the harbour (Fig 5.2 see appendix) constrains the morphology and extent of the proposed tuff ring. The maximum thickness of the trachytic lapilli tuff occurs on the eastern coast of Onawe peninsula (Fig 5.2 see appendix) (Fig 5.20 see appendix) where thicknesses reach up to ~3.3 m. Outcrops also occur between Petit Carenage Bay and French Farm Bay (~1m thick)(Fig 5.26 see appendix), between Lushington and Takamatua Bays (~70 cm thick) (Fig 5.24 see appendix) and the road cut between Barry's and French Farm Bays (~1.6m thick) (Fig 5.26 see appendix)(See Fig 5.2 appendix for localities). Bedding measurements around the harbour allow the extent and shape of the tuff ring to be constrained: The northern flank is located at Onawe peninsula and dips 12˚ to the north and the eastern flank is observed at Lushington Bay with beds dipping 10˚ to the east south east. Deposits at Petit Carenage Bay dip to the West at about 12˚ and represent the western flank and the outcrop between French farm Bay and Barrys Bay dips to the north west outlining the north western flank. The shallow nature of these dips (< 25˚) indicates this formation was a tuff ring rather than a cone and suggests a central vent located to the south east of Onawe Peninsula (Fig 5.2 see appendix). The maximum extent of the eruption is also estimated by correlating the outer contacts of both the trachyte lapilli tuffs and trachyte tuffs. Evidence of slumping is observed at the upper contact of the deposit exposed on Eastern Onawe Peninsula with a scour like structure containing large clasts of redeposited fill (Fig 5.23). Slumping is characteristic of subaerial tuff rings as they are relatively unstable due to their initial unconsolidated nature.

The trachyte tuff, best exposed at Onawe Peninsula (Fig 5.2 see appendix) is part of the Lushington Breccia Formation (*al*). This unit is comparable to distal surge facies on tuff cones on Cheju Island, Korea (Sohn and Chough 1989) and is interpreted as representing a medial to distal wet surge deposit from an emergent subaerial tuff ring (Table 6.2 see appendix). It is also proposed that the deposit represents the transition into a more explosive phase of volcanism, resulting from increased water access to the active tuff ring vent. These interpretations are based on the dominance of fine material, the finely laminated planar nature of the deposit and the presence of accreationary lapilli, pinch and swell structures and ripples (Fig 5.7) (Fig 5.8). These features are indicative of medial to distal tuff ring facies as grain size decreases and planar or sandwave bedding becomes well developed with distance from the vent (Sohn and Chough 1989). This facies change results from a decrease in particle concentrations causing tractional processes become more dominant.

The thickness and spatial distribution of the deposits within the harbour (Fig 5.2 see appendix) supports the morphology and extent of the tuff ring. The northern flank of the tuff ring is located at Onawe Peninsula (Fig 5.2 see appendix) the deposits reaches thicknesses up to 2.7m (Fig 5.20 see appendix). The beds of this unit dips 12˚ to the north; however these deposits flatten out abruptly as you move northward through the sequence. The scoured nature of the bottom contact (Fig 5.23) indicates slumping and this could possibly account for increased water access into the vent and the increased explosivity and decreased grain size of the deposit. The trachytic tuff also occurs between French Farm and Barrys Bay (~1 m) (Fig 5.2 see appendix) (Fig 5.26 see appendix).

The absence of marine sediments and/or coastal reworking of the above trachytic pyroclastics possibly indicates rapid burial as a result of sustained eruptions. This rapid deposition would have limited marine deposition and/or reworking of the early subaqueous deposits, eventually resulting in emergent volcanism.

The coherent lava of the Tikao Dome supports an origin of proximal dome facies (Table 6.2 see appendix). It is not vesicular, and has a generally similar chemistry, texture (Fig 5.1 see appendix), low crystal content (Fig 5.17a) (Fig 5.17b) and similar stratigraphic (Fig 4.1) and spatial relationships (Fig 5.2 see appendix) to the trachyte deposits of the Lushington Breccia Formation (*al*).

The lava is exposed between Tikao Bay and Petit Carenage Bay reaching thicknesses of ~ 60m (Fig 5.2 see appendix). However, it is unclear whether Tikao Dome was erupted from the same location as the trachytic pyroclastics in the form of an effusive plug at the end of the explosive phase of volcanism, or whether it was erupted from a separate, though nearby, eruptive centre. Based on its proximity to the trachytic pyroclastics, and on the observed stratigraphic relationships in which the dome is found on top of a small deposit of trachytic lapilli tuff, we prefer a model in which the dome is erupted from the same eruptive centre as the trachytic pyroclastics. Given its chemistry, which is slightly less evolved than the early trachytic pyroclastics (Fig 5.1 see appendix) we propose that the Tikao Dome may represent effusion of magma sourced from a lower level in the trachytic magma chamber, and from the same (or very proximal) vent as that for the trachytic pyroclastics of the Lushington Breccia Formation (*al*).

6.3 Interpretation of the mafic facies

The majority of mafic pyroclastic facies observed around Akaroa harbour represent deposits associated with basaltic scoria cones that locally interacted with seawater, as well more voluminous effusive lava flows and associated tuffs. The basaltic pyroclastic deposits of brecciated basaltic lapilli tuff, spatter, mixed scoriaceous deposits, non flattened scoriaceous deposits and ash rich deposits are proposed to make up parts of scoria cones located at mid and north Onawe Peninsula, Hammond Point, Robinsons Bay, Childrens Bay, and Anchorage Bay (Fig 5.2 see appendix). Bedding measurements depict the inferred centres of these cones, which are often eroded.

The brecciated basaltic lapilli tuff of the French Hill Formation (*af*), best exposed at Northern Onawe Peninsula is interpreted as representing a phreatomagmatic ash breccia of the basal outer wall facies of a scoria cone (Fig 6.1)(Table 6.2 see appendix). This interpretation is based on the fine grained, sub-angular to sub-rounded and ragged nature of clasts (Fig 5.34a)(Fig 5.34b)(Fig 5.34c) and presence of accretionary lapilli, which is characteristic of phreatomagmatic deposits. Also abundant alteration textures and palagonisation are apparent in thin section (Fig 5.34c). These deposits occur around the outer base of scoria cones located on the Northern end of Onawe Peninsula (~0.3 m), Hammond Point, Robinsons Bay (~ 0.3 m), Childrens Bay and Wainui Bay. The thicknesses of the other deposits are unknown, as only the top contact is observed on the shore platforms.

Spatter deposits of the French Hill Formation (*af*), best exposed at Robinsons Bay (Fig 5.2 see appendix), are interpreted as representing a Hawaiian type fire fountaining style of activity. These deposits belong to the lower crater facies (Fig 6.1) (Table 6.2 see appendix) formed during the early stages of scoria cone formation. This is based on the densely welded spatter and ribbon bomb rich nature of the deposits (Fig 5.35a), indicative of a hot magmatic eruption with clasts still molten on landing. This is further supported by thin sections that show the matrix consists of sub-angular, ragged glass shards and flattened scoria (Fig 5.35b)(Fig 5.35c), indicative of a hot magmatic eruption. The layered nature of these deposits supports a fountaining style of eruption with pyroclastics falling out in layers. These deposits are found at scoria cones on mid and Northern Onawe Peninsula (~0.9 m thick), Hammond Point, Robinsons Bay (~0.8 m), Childrens Bay and Anchorage Bay (Fig 5.2 see appendix).

Mixed scoriaceous deposits are interpreted as representing a transitional style of eruption between Hawaiian and strombolian styles and are typical of the mid crater facies (Fig 6.1)(Table 6.2 see appendix). This interpretation is based on the deposits' proximity to the inferred vents and the presence of fluidal ragged clasts as well as more solidified inflated bomb morphologies (Fig 5.36a)(Fig 5.36b). The deposits are partially welded although individual clasts are discernible, which is indicative of a transitional eruption style. In thin section some scoriaceous clasts are flattened with elongate vesicles (Fig 5.36c)(Fig 5.36d) indicative of the clasts being partially molten on landing. These deposits are found at scoria cones at mid and North Onawe Peninsula (~0.8 m thick), Hammond Point, Robinsons Bay (~0.9 m thick), Childrens Bay and Wainui Bay (Fig 5.2 see appendix).

Non-flattened scoriaceous deposits are interpreted as representing strombolian type deposits of the upper crater facies (UCF)(Fig 6.1) of a scoria cone (Table 6.2 see appendix). This is based on the non welded nature of the deposit and the rounded bread crust bombs in a poorly sorted lapilli and ash matrix, which is indicative of strombolian deposits. These deposits are found at scoria cones at North Onawe Peninsula (~1.6 m thick), Hammond Point, Robinsons Bay (~0.9 m thick), Childrens Bay and Wainui Bay (Fig 5.2 see appendix).

Ash-rich deposits are interpreted as representing proximal to medial ash fall layers (Table 6.2 see appendix) that are commonly observed on the tops and outer flanks of scoria cones. This interpretation is based on the well sorted nature of the deposits, which are also comprised of alternating layers of ash and lapilli sized spatter clasts; another typical feature of ash fall out deposits at scoria cones worldwide. These deposits are found at scoria cones at northern Onawe Peninsula (~0.6 m thick), Hammond Point, Robinsons Bay (~0.6 m thick), Childrens Bay and Wainui Bay (Fig

5.2 see appendix).

The mafic facies not associated with discrete scoria cones consist of voluminous lava flows and the polylithic welded tuff exposed on southern Onawe Peninsula. The polylithic welded tuff represents a proximal hyaloclastic auto breccia of a mafic lava flow. This deposit formed from the interaction of lava flows with sea water. The abundance of country rock clasts within the unit suggests the deposit also interacted with the wet sea floor causing the incorporation of Torlesse sandstone lithologies (Fig 5.30a)(Fig 5.30b)(Fig 5.30c). The hawaiite lava flow of the Harbour Formation (*ah*) is only observed on the eastern side of Southern Onawe Peninsula. This blue to black, olivine and plagioclase phenocryst bearing porphyritic flow is interpreted as representing a coherent lava facies. The proximity to the polylithic welded tuff on the western side of Onawe Peninsula and the dip of the flow to the north east may indicate that this unit represent an emergent uncontaminated part of the flow or flow field.

The French Hill Formation (*af*) consists of lava flow fields in which flows commonly overlap and discrete lava flows associated with scoria cones, with lava commonly breaching cone bases. Lava flows are interpreted as dominantly pahoehoe style flows (Table 6.2 see appendix). Although ropey textures are not commonly observed due to poor preservation of flow tops, the deposits often have distinctive flow lobes. The deposits do not display clinkery flow margins as would be expected with a'a flows, and while some clinker might be expected to be removed by erosion, it’s total absence suggests against a'a morphologies.

The lava flows of the French Hill Formation (*af*) are dominantly comprised of picritic basalt and olivine alkali basalt however minor amounts of hawaiite, Mugearite and Benmoreiite are also present (Fig 5.1 see appendix). There is no clear correlation between lava flow petrology and the vent type (ie scoria cone or larger effusive vent). However, phenocryst assemblages do vary in lava flows observed around the harbour. Picritic flows contain olivine, clinopyroxene and plagioclase phenocrysts, whereas olivine alkali basalt, hawaiite, mugearite and benmoreiite flow only contain Olivine and plagioclase phenocrysts. This indicates that either atleast two magma sources are present or that distinctly different sections of the magma chamber were being erupted.

6.4 Interpretation of the Intrusive deposits

Trachytic dykes are intruded throughout the early formations of Akaroa Volcano. Three distinct dyke types occur, of these two are aphyric (Fig 5.11) (Fig 5.13) and the other is porphyritic. These differences in textures indicates very different crystallisation histories suggesting either the intrusion of separate batches of magma or different layers of a stratified magma chamber were intruded.

The only plutonic rocks on Banks Peninsula are located on Onawe Peninsula (Fig 5.2 see appendix). Both the Duvauchelle Gabbro (*ad*) and Onawe Syenite (*ao*) are main phase deposits thought to be the remnants of magma chambers which ascended, possibly due to thermal instabilities. The gabbro was most likely intruded before the syenite based on its small extent and distribution, however the contact is obscured so the exact nature of the relationship is unclear.

7. History of development, the early stages of Akaroa Volcano

The early stages of development of Akaroa Volcano, provide a sequence through the emergent stages of volcanism from subaqueous to emergent. The first deposits we see (Harbour Formation *ah*) indicate that initial volcanism at Akaroa was mafic and began in a subaqueous to emergent environment. Hyaloclastic auto breccias formed as initial lava flows interacted with water and the sea floor, resulting in hydrofragmentation and the incorporation of local country rock lithologies (Fig 5.30c). A massive lava flow stratigraphically above the hyaloclastites indicate that these flows then became locally emergent (Onawe Peninsula) (Fig 7.1 see appendix).

A large trachytic centre (Lushington Breccia Formation *al*) then developed to the south east and lava extruded sub aqueously forming a hyaloclastite coulee (Fig 7.2 see appendix), with the thickest deposit at what is now Lushington Bay (Fig 5.2 see appendix). An emergent trachytic tuff ring formed on the flanks of the coulee as magma interacted with small amounts of ground/seawater, and explosive eruptions began depositing high particle concentration surges (Fig 7.4 see appendix see appendix). Slumping of the flanks of the tuff ring occurred (Fig 7.4 see appendix) due to instabilities caused by steep topography and the relatively wet nature of the sediment. Slumping allowed increased water interaction and produced low particle concentration surges (Fig 7.4 see appendix).

Contemporaneous with the Lushington Breccia Formation (*al*) was the basaltic volcanism of the early French Hill Formation (*af*). These deposits consisted of a series of discrete scoria cones and small associated lava flows (Fig 7.4 see appendix)(Fig 7.5 see appendix). Mafic eruptions continued, and migrated around the central trachytic deposits forming a series of discrete scoria cones (Fig 7.6 see appendix). Small lava flows associated with these local scoria cones filled valleys between inferred eruptive centres (Fig 7.5 see appendix).

Trachytic volcanism became less voluminous and explosive, with degassed magma extruded as a dome at Tikao Bay (*at*), possibly from the same eruptive centre as the earlier trachytic pyroclastics (Fig 7.7 see appendix). This shift in eruption style could be due to the volcano becoming emergent and no longer interacting with seawater. Extensive basaltic activity continued with voluminous lava flows being the dominant style of volcanism (Fig 7.7 see appendix).

Following the emplacement of the early stage deposits of Akaroa Volcano there was a pause in volcanic activity, marked by an erosional unconformity. This temporary cessation of volcanism was succeeded by the intrusion of a multitude of predominantly trachyte dykes into the earlier formed deposits (Fig 7.8 see appendix). Subsequently the main shield forming stage of volcanism was erupted. This later French Hill Formation (*af*) was dominated by voluminous basaltic lava flows and cones; with minor volumes of trachyte forming domes also emplaced at this time. This main phase of activity at Akaroa Volcano was characterised by emplacement of voluminous lava flows that generally dip away from the harbour.

Plutonic deposits were then intruded into the deposits of Akaroa Volcano at Onawe Peninsula (Fig 7.9 see appendix). The Duvauchelle Gabbro was mostly likely intruded first as it only occurs as a narrow strip on Onawe Peninsula. Whereas the Onawe Syenite occurs as a large dome shaped intrusion (Fig 5.2 see appendix).

After volcanism ceased erosion was the dominant processes that reshaped the volcanic complex. Topographical lows were preferentially eroded to form well developed channels the biggest of which is Akaroa Harbour. Scoria cones were also preferentially eroded creating many of the bays both within the inner harbour and on the outer flanks of the edifice. The combination of the primary constructional volcanic features and the secondary erosional features form the unique landscape of Akaroa Volcano observed today.

8. Conclusion

This study provides a rare look into the early eruption styles of a large basaltic to trachytic strato-shield volcanic complex. Detailed field mapping, petrography and stratigraphic logging reveal that.

Similar to Lyttelton Volcano early emergent Akaroa is a complex stratoshield volcano with multiple centres varying in composition, eruptive style and depositional processes. This diversity in volcanism primarily reflects composition but is also strongly influenced by the degree of water interaction.

A large trachytic centre dominated the early stages of Volcanism at Akaroa Volcano. This extensive centre had multiple phases of activity and displayed transitions in style, both temporally and spatially. Temporal transitions in style consisted of changes from a subaqueous to emergent hyaloclastite dome, to an explosive phreatomagmatic trachyte tuff ring to an effusive trachytic dome (Fig 7.1 – Fig 7.7). Whereas spacial transitions consisted of lateral facies variations within the pyroclastic surge deposits reflecting 'en route' changes in deposition.

Basaltic volcanism of emergent Akaroa Volcano consisted of less voluminous discrete cones, small associated lava flows and more extensive lava flows. These smaller vents migrated the central trachytic unit and formed multiple volcanic islands within the area presently exposed as Akaroa Harbour. Volcanic cones consisted of various eruptive products with a progression from low angle phreatomagmatic palagonite rich lapilli tuffs to steeper bedded spatter and bomb dominated scoria cone deposits. This transition in facies is explained as individual volcanoes becoming emergent and therefore having less interaction with seawater. These discrete centres later coalesced through deposition of the more extensive lava flows forming the early volcanic complex of Akaroa Volcano.

Sea levels during this period of formation were similar to today (Martin 2000). However the absence of marine sediments and coastal reworking within and between the volcanoclastic deposits supports a largely subaerial deposition despite evidence for periods of phreatomagmatic activity. The units that were deposited underwater must have rapidly been buried to prevent marine deposition or reworking.

Erosional processes dramatically reshaped the early stage deposits observed in the inner harbour. Based on the location of volcanic centres around the harbour (Fig 5.2) the channel that forms the main inlet most likely represents an eroded topographical low between basaltic vents. Many of the irregular bays in the present day harbour were formed by preferential erosion of scoriaceous units, as indicated by remnant exposures in the coastal cliffs. Whereas lavas tend to form the headlands, this resulted in the irregular shape of the Akaroa Volcanoes inner harbour observed today.

The Main stage of volcanism is defined by the onset of large volume of basaltic lava flows and the development of a central vent (Dorsey 1988, Shelley 1992). However, the main stage volcanism is relatively poorly studied and it is not well known whether the central vent model or multiple vent model similar to Lyttleton volcano (Hampton 2009) is a more suitable for Akaroa Volcano as a whole.

We suggest future work should be focused on the main stage of Akaroa volcano to distinguish primary and secondary volcanic features and to determine the relationship of the multitude of trachytic domes observed in the later successions of the main phases of volcanism at Akaroa Volcano.

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10. Appendix

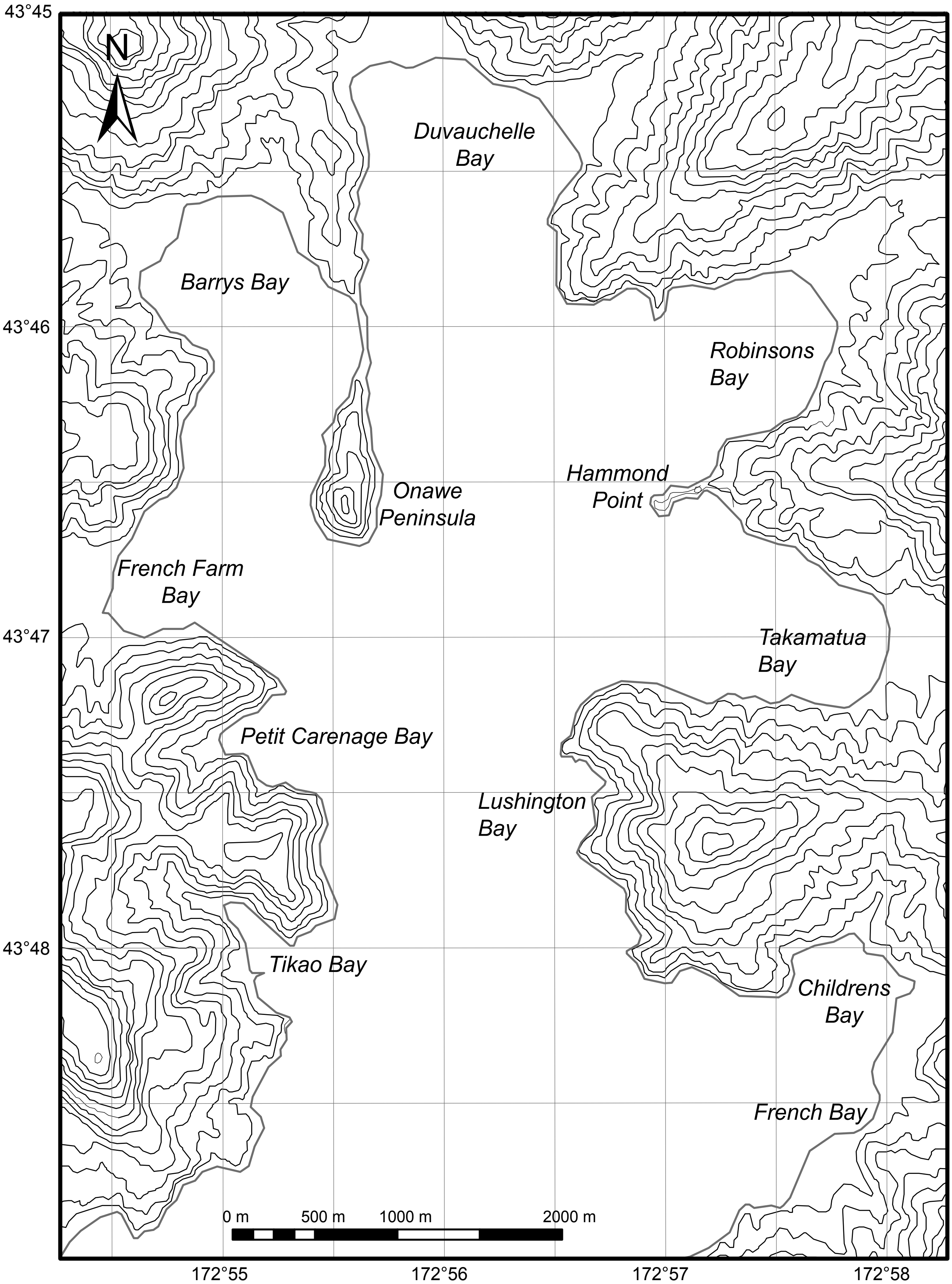

Fig 3.1 Akaroa Harbour field work localities. Topographic contours are at 10 m intervals

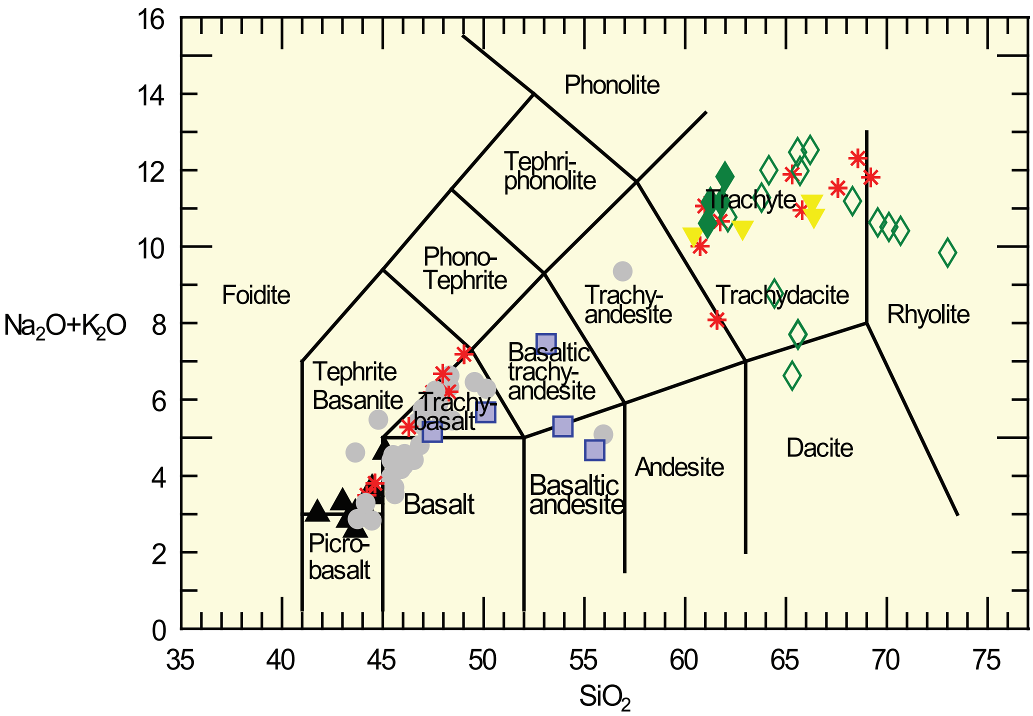

Figure 5.1 TAS diagram of whole-rock major element variation for the volcanic and plutonic rocks of Akaroa.

Key

- Onawe Syenite (*ao*)
- Duvachelle Gabbro (*ad*)
- French Hill Formation (*af*)
- Tikao Trachyte (at)
- Lushington Breccia (*al*)
- Harbour Formation (*ah*)
- Dykes

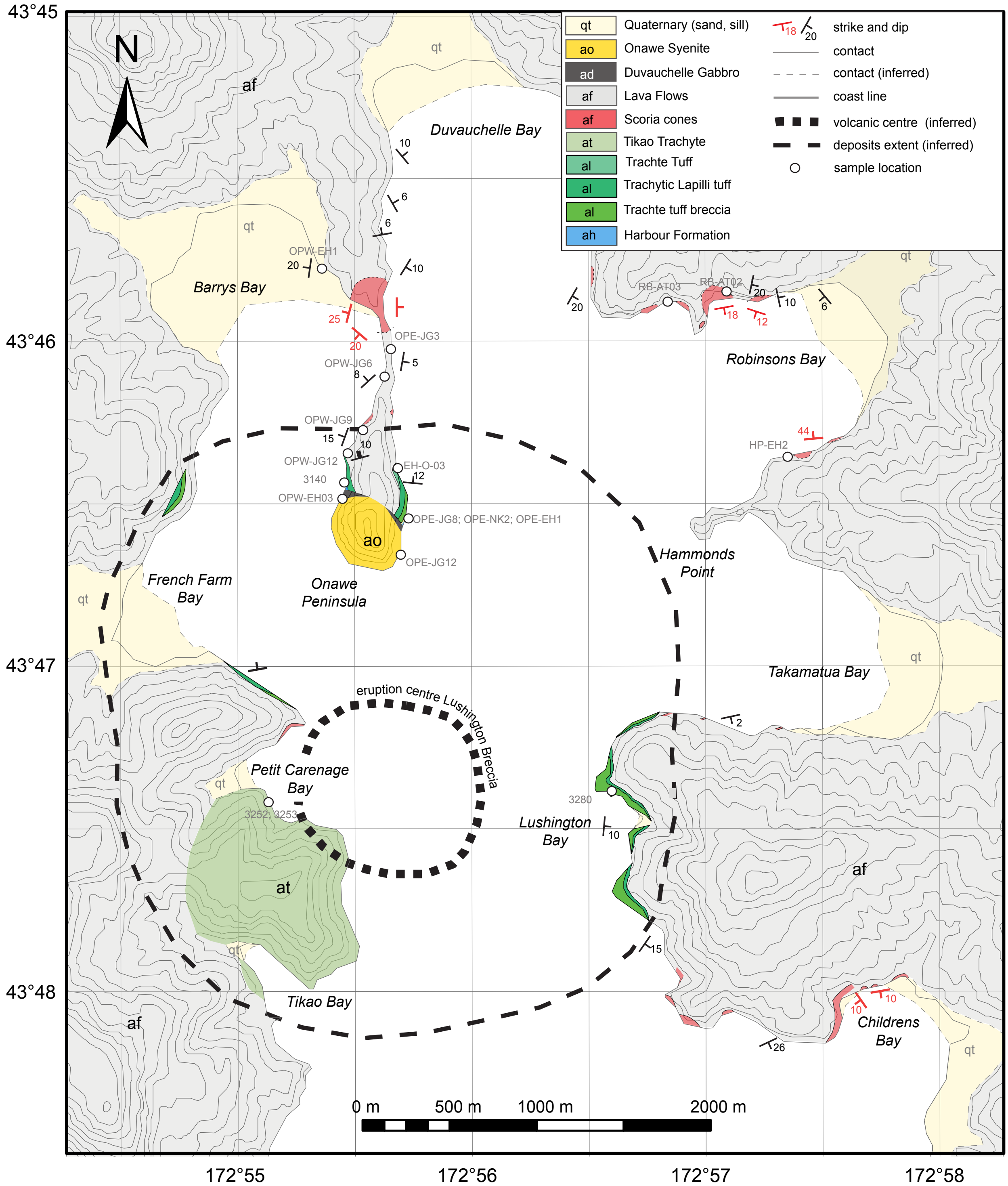

Fig 5.2 Simplified geological map of the central section of Akaroa Volcano. The map is a compilation of new field observations (this thesis and Hartung 2011) and interpretations and previous geological maps created by Dorsey (1988) and Sewell (1988). Topographic contour lines are in intervals of 10 meters. Sample numbers correspond to representative samples described in this thesis. For full sample localities see appendix. Red strike and dip symbols refer to cinder cone strike and dips. Thin dashed lines represent inferred contacts between different deposits. Thick dashed black lines circle the eruption centre and outer limits of the Lushington Breccia Formation (*al*) eruption inferred from field messurements and deposit localities.

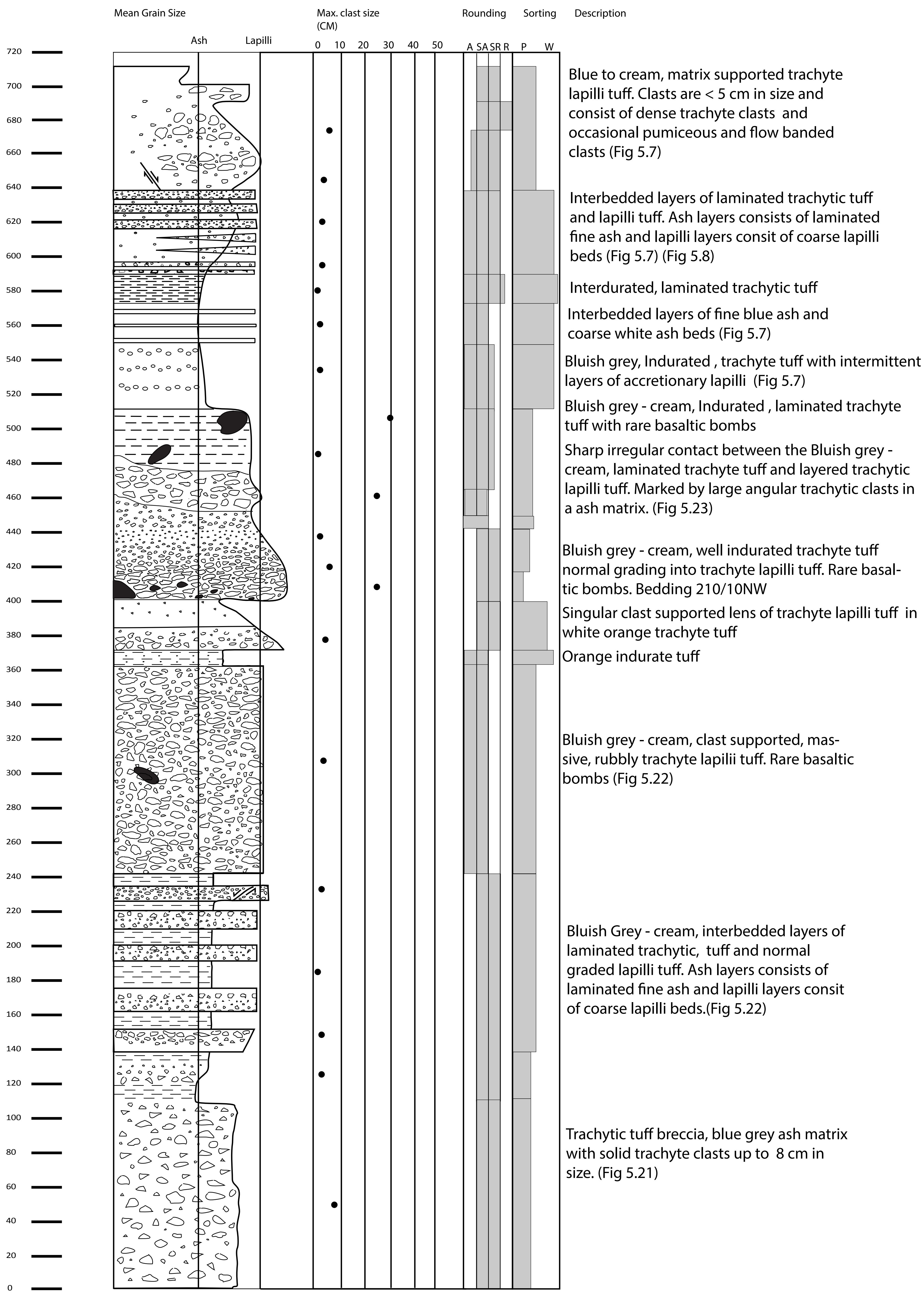

Fig 5.20 Stratigraphic log of the continiuos stratigraphic secquence on the eastern side of Onawe Peninsula. The logged sequence begins on the southern end of Onawe Peninsula and continiues north up through the whole lushington breccia formation sequence.

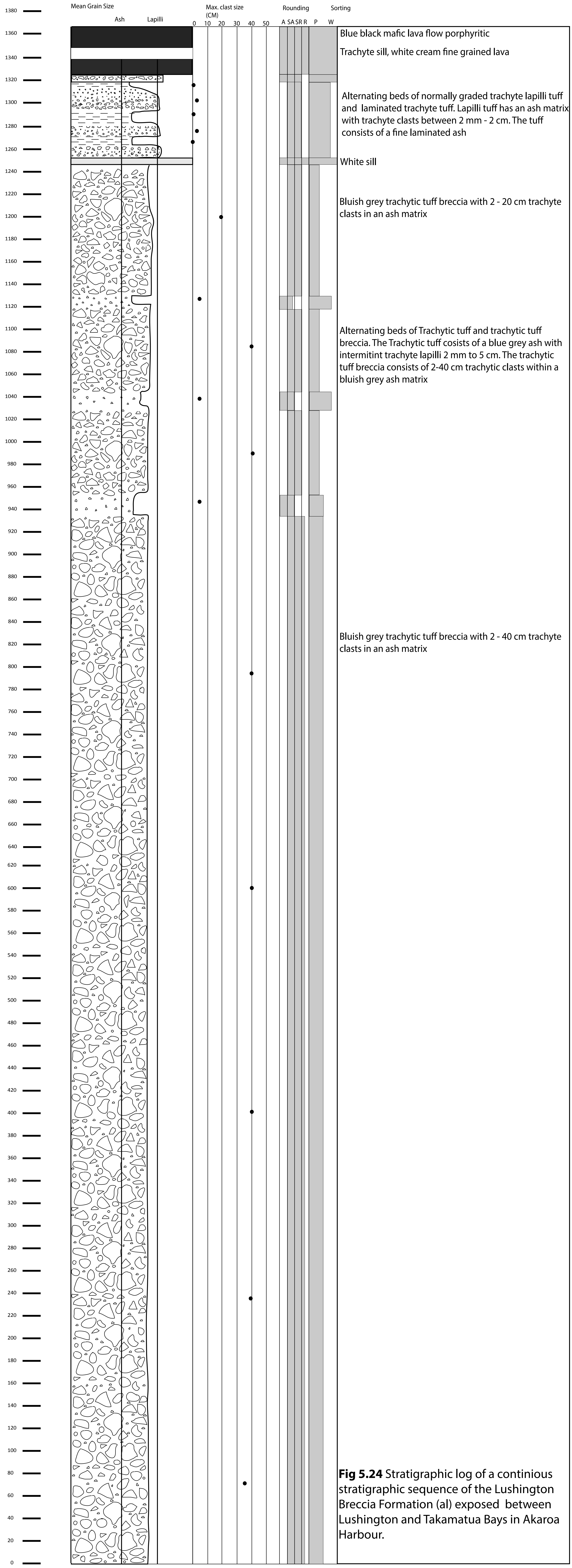

Fig 5.24 Stratigraphic log of a continious stratigraphic sequence of the Lushington Breccia Formation (al) exposed between Lushington and Takamatua Bays in Akaroa Harbour.

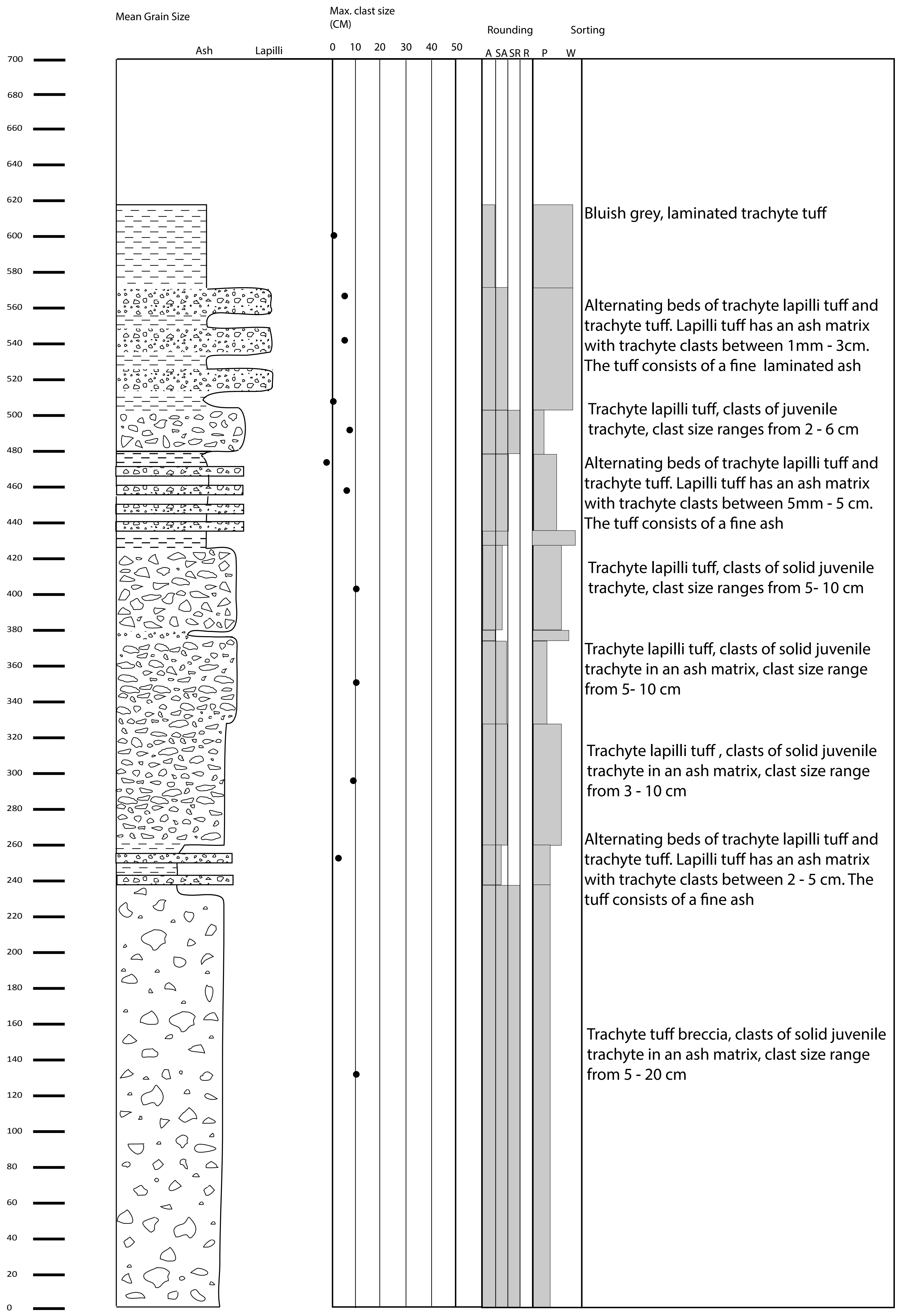

Fig 5.26 Stratigraphic log of a continiuos stratigraphic sequence of Lushingoton breccia formation exposed on a road cut between French Farm Bay and Barry's Bay.

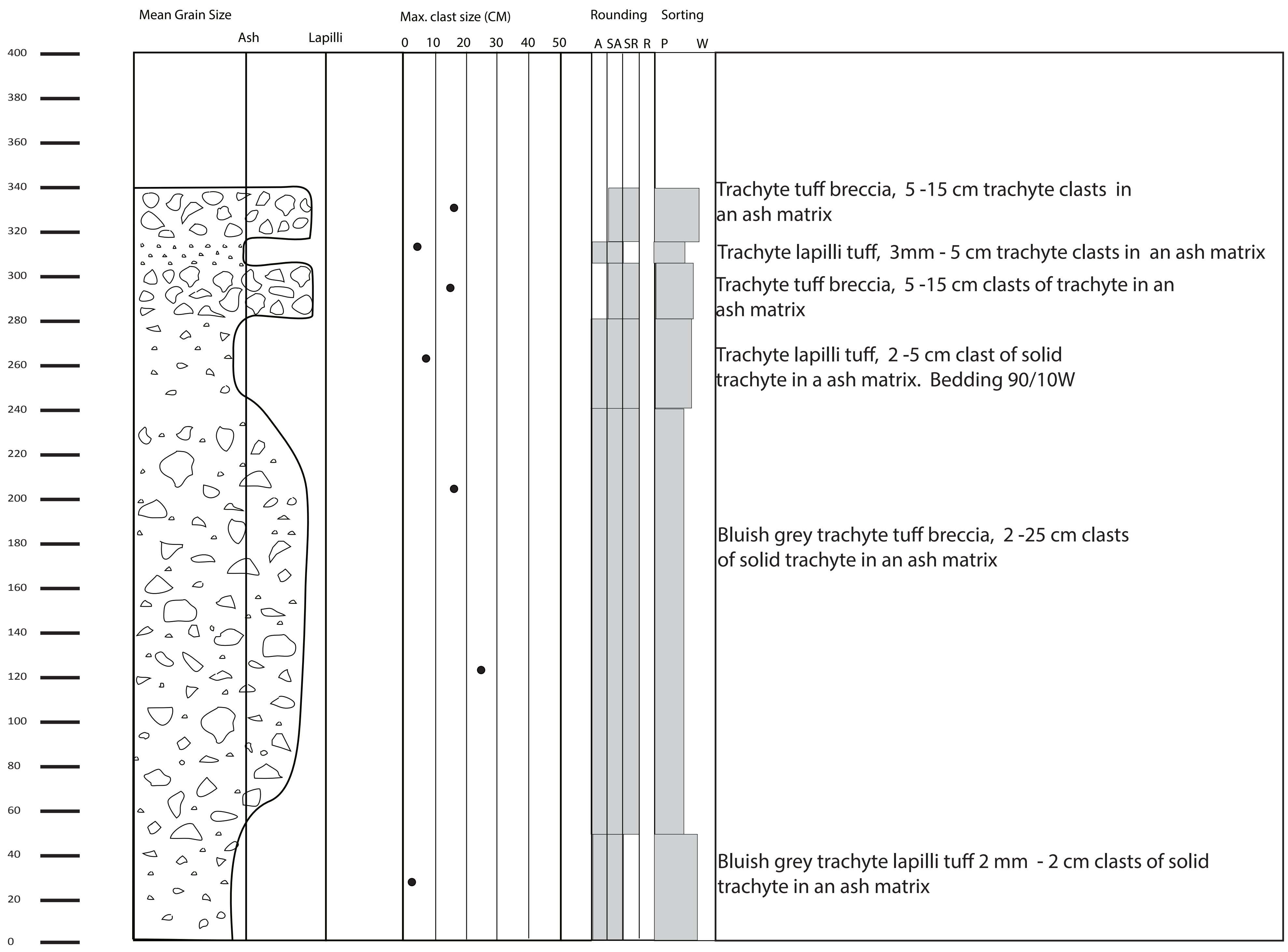

Fig 5.27 Stratigraphic log of the continiuos stratigraphic secquence exposed between French Farm Bay and Petit Carenage Bay.

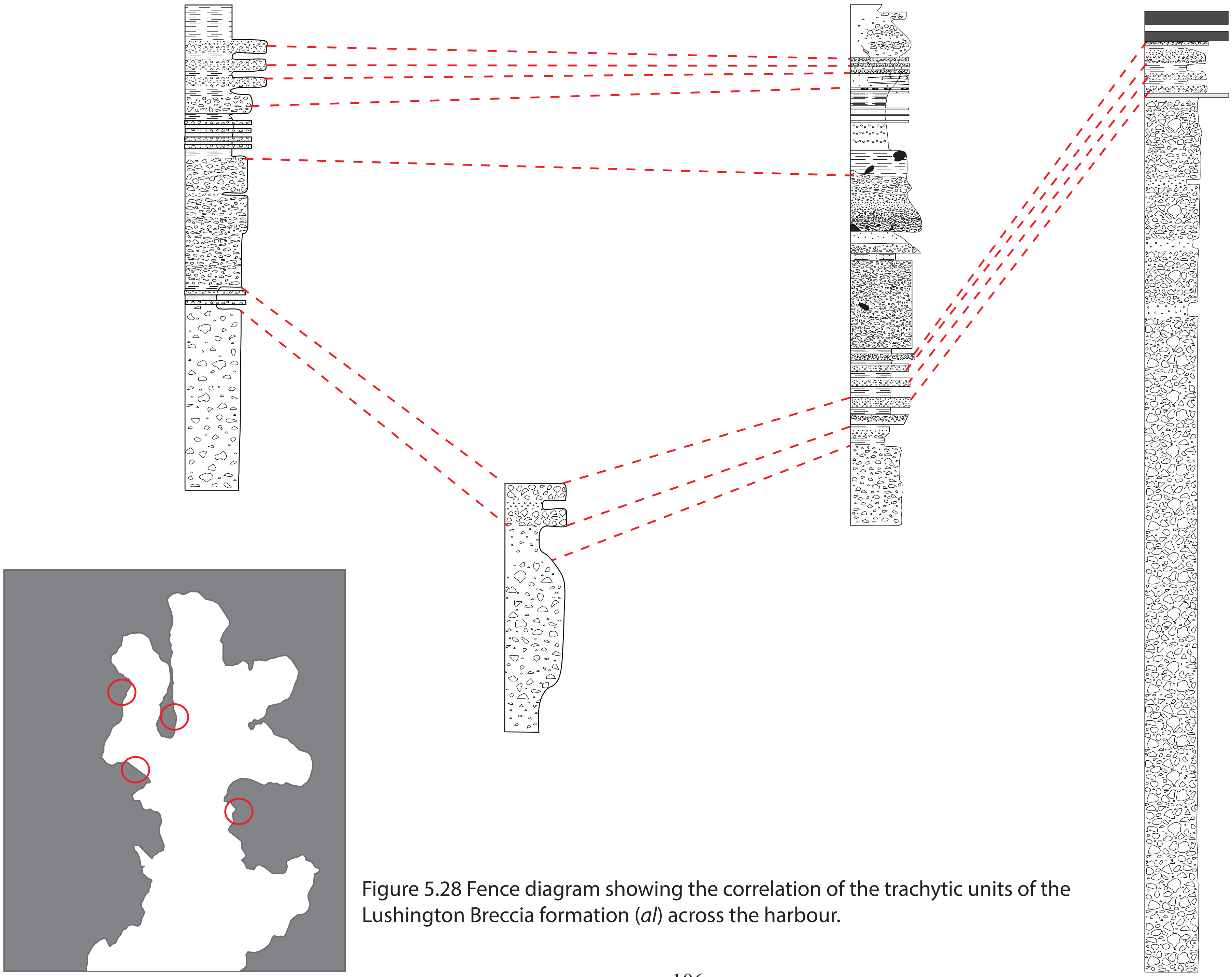

Figure 5.28 Fence diagram showing the correlation of the trachytic units of the Lushington Breccia formation (*al*) across the harbour.

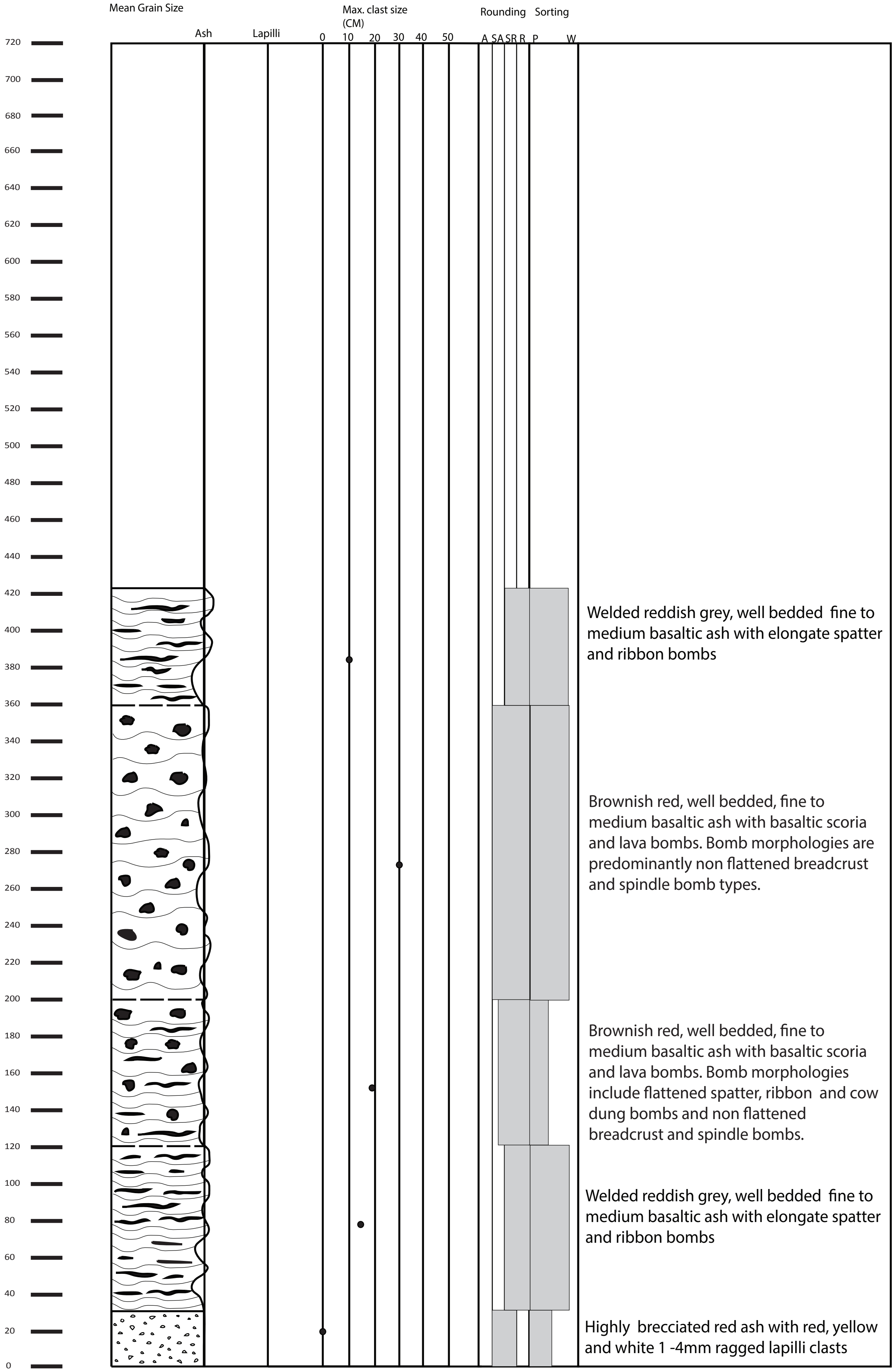

Figure 5.39 Stratigraphic log of the Northern Onawe sequence through a scoria cone of the French Hill Formation (*af*)

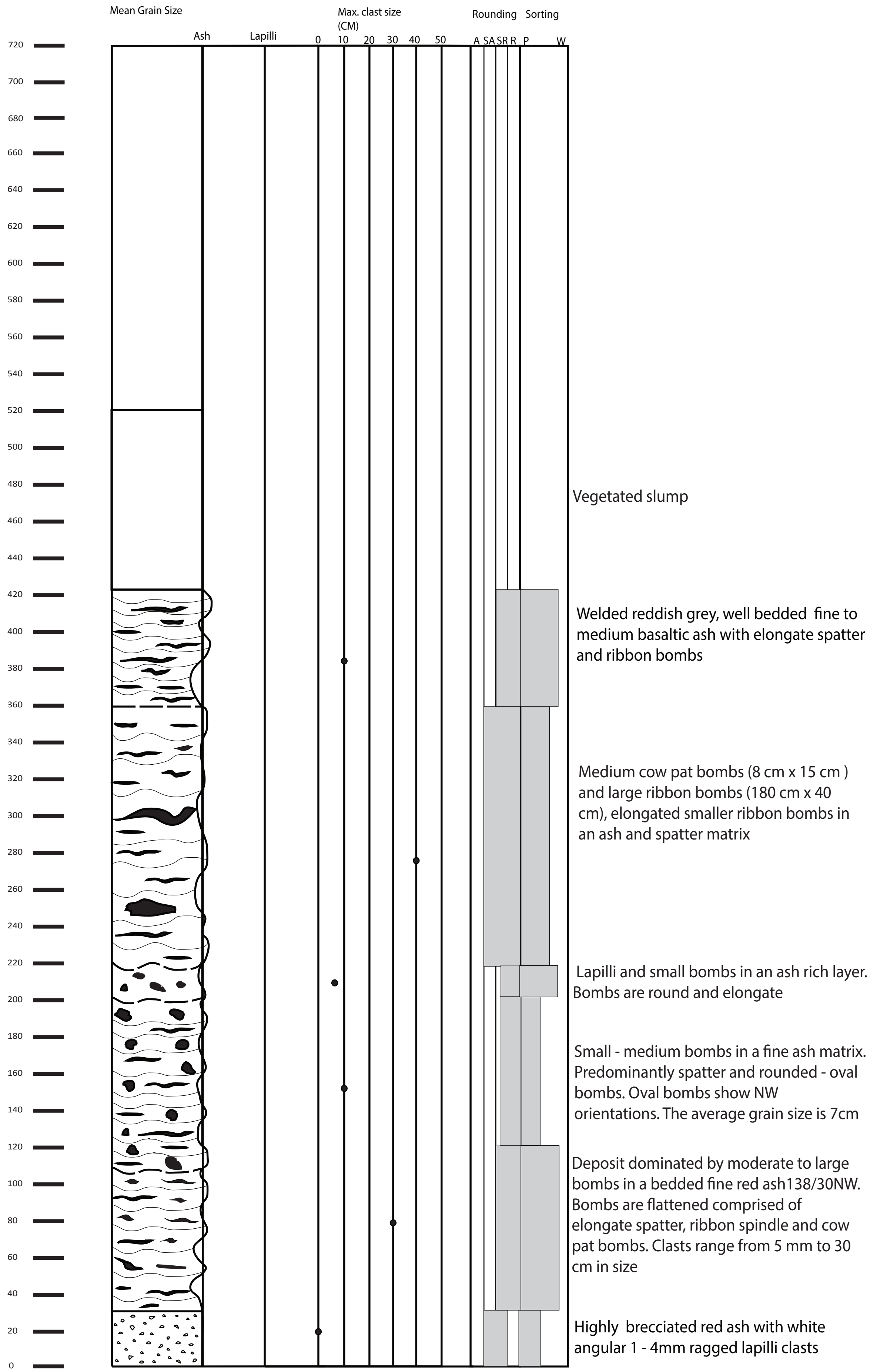

Figure 5.40 Stratigraphic log of a scoria cone sequence of the French Hill Formation (*af*) from Robinson's Bay

	Lava rock	Tuff breccia	Lapilli tuff	Tuff	Interpretation/ formation process	Facies assemblages
Massive		TTB1			Hyaloclastite coulee carapace	Dome proximal
Disorganised beds			TLT1		Proximal wet surge	Proximal to medial tuff ring facies
Massive			TLT2		Medial wet surge	Medial to distal tuff ring facies
Planar Beds				TT1	Distal wet surge	Distal tuff ring facies
Coherent felsic	TLR1				Exogenous lava dome	Proximal coherent dome facies
Brecciated			BLT1		Basal phreatomagmatic	Scoria cone basal outer wall facies
Spatter			BLT2		Hawaiian fire fountaining	Scoria cone lower crater facies
Mixed scoriaceous beds		BTB1			Transitional	Scoria cone mid crater facies
Non flattend scoriaceous beds		BTB2			Strombolian	Scoria cone upper crater facies
Layered				BT1	Proximal to medial ash fall	Scoria cones outer flank facies
Coherent mafic	BLR1				Pahoehoe flows	Coherent lava flow facies

Fig 6.9 Lithofacies associations table describing the deposits, formation processes and facies assemblages of the deposits of Early stage Akaroa Volcano.

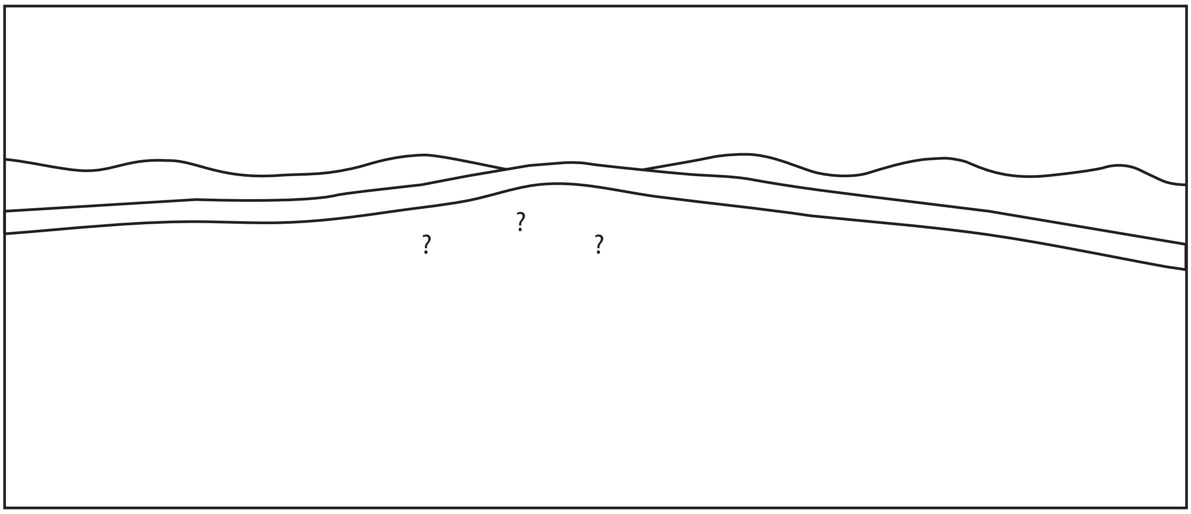

Fig 7.1 Stage 1: Intial mafic lava flows become emergent

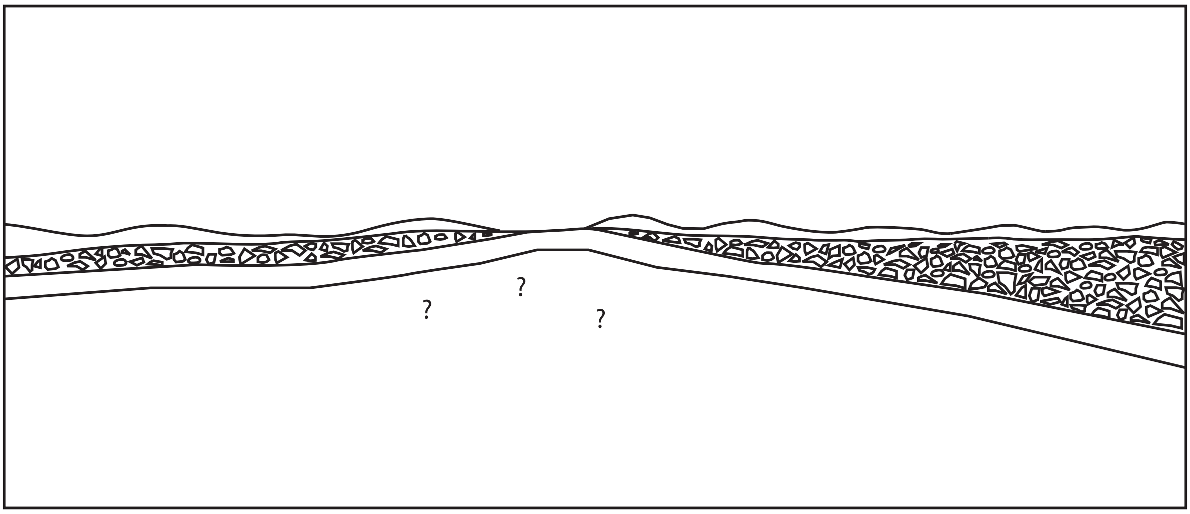

Fig 7.2 Stage 2: Activity transitioned to a trachytic composition and a large hyaloaclastite coulee was formed

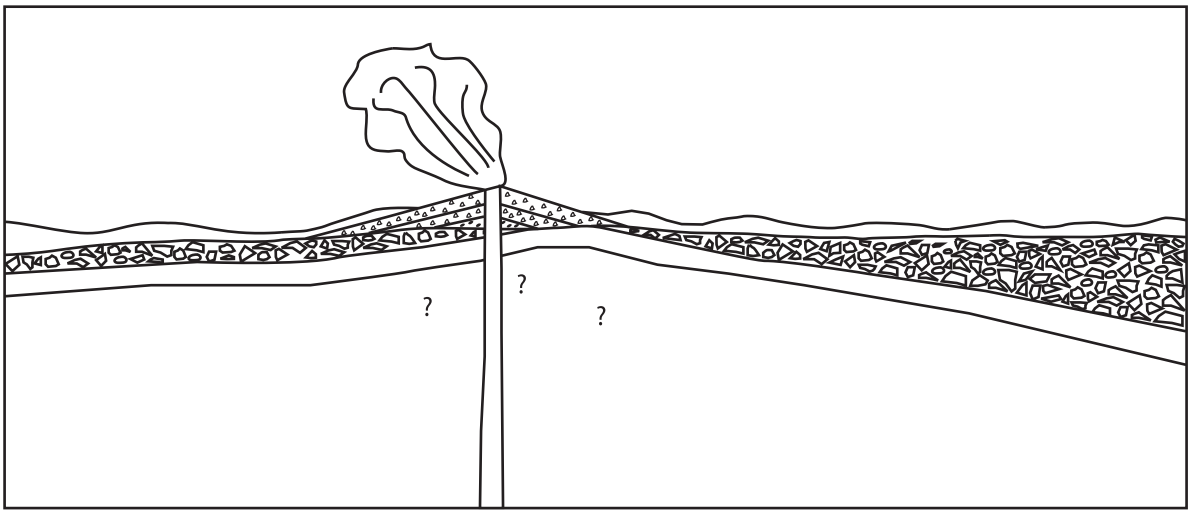

Fig 7.3 Stage 3: Emergent trachytic tuff ring developed ontop of the trachytic coulee

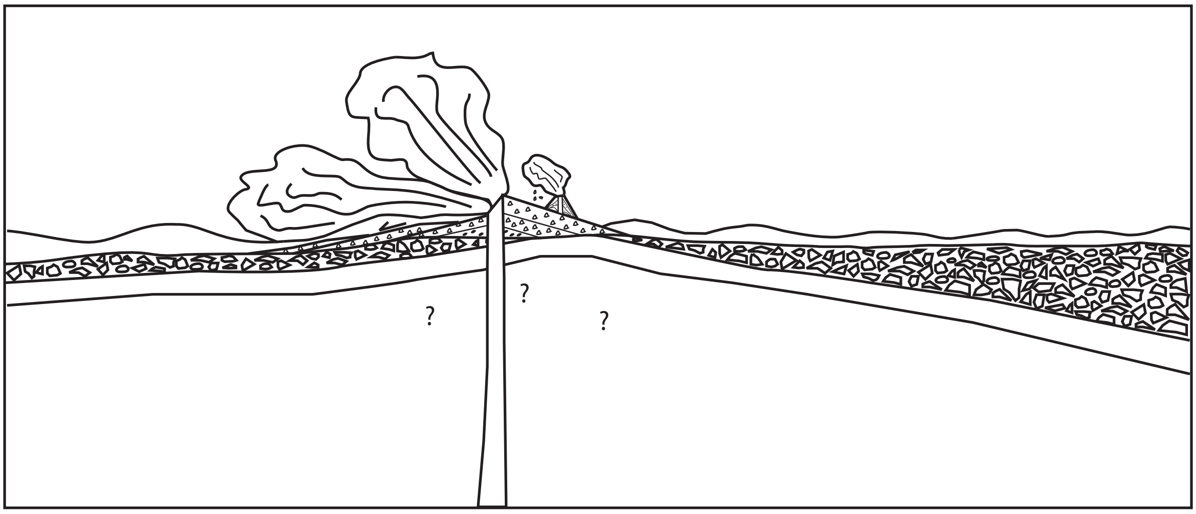

Fig 7.4 Stage 4: Slumping of the flanks of the tuff ring occurred allowing increased water interaction. This resulted more phreatomagmatic eruptions forming fine grained surge

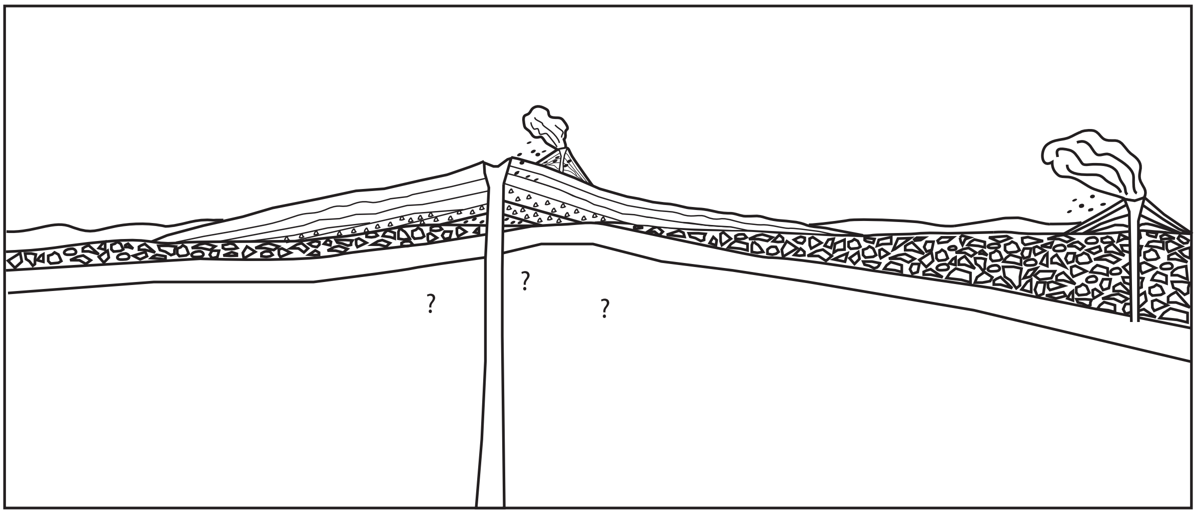

Fig 7.5 Stage : Sustained phreatomagmatic eruptions formed fine grained surge deposits (al) increasing the size of the tuff ring. Mafic volcanism (af) was also occuring forming discrete scoria cones.

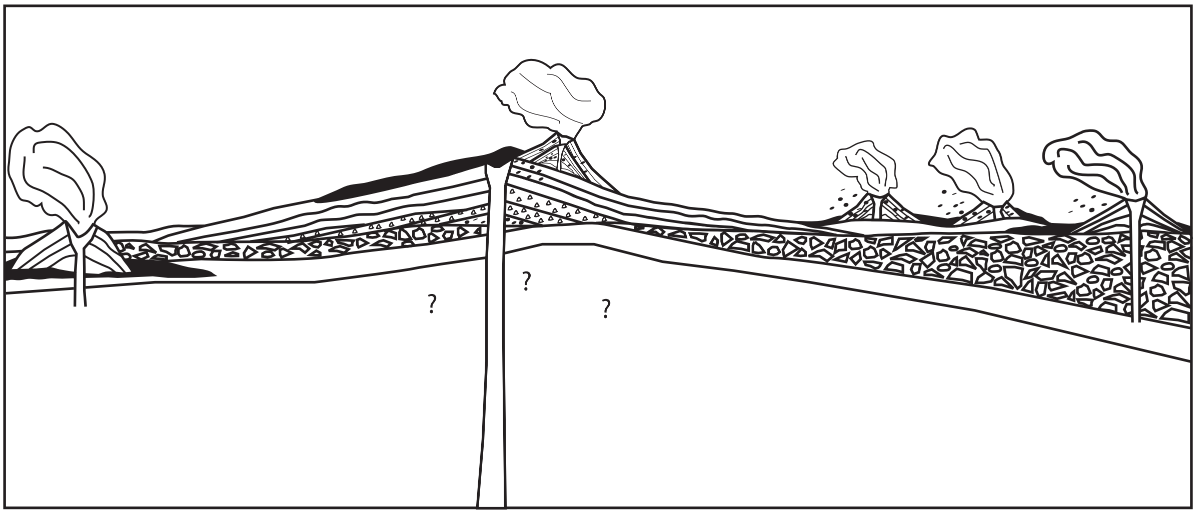

Fig 7.6 Stage 6 : Trachytic volcanism ceased as mafic volcanism became more extensive. A series of discrete scoria cones and associated lava flows formed as well as more voluminous lava flows (af).

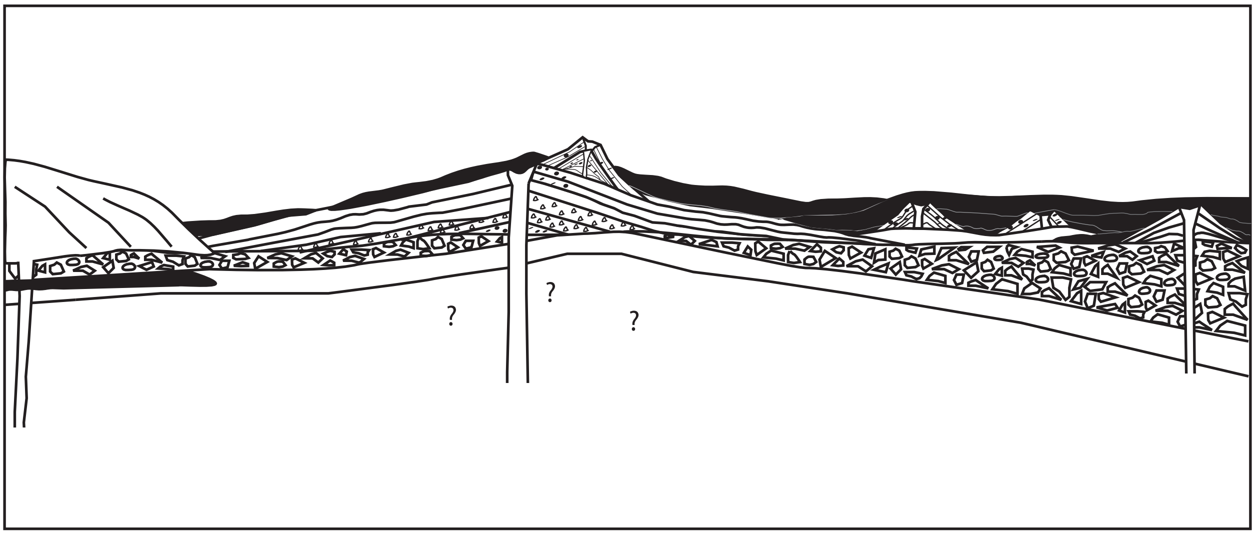

Fig 7.7 Stage 7: A trachytic dome developed to the west, degassed magma extruded as a dome at Tikao Bay (at). Extensive basaltic activity continiued with voluminous lava flows being the dominant style of volcanism.

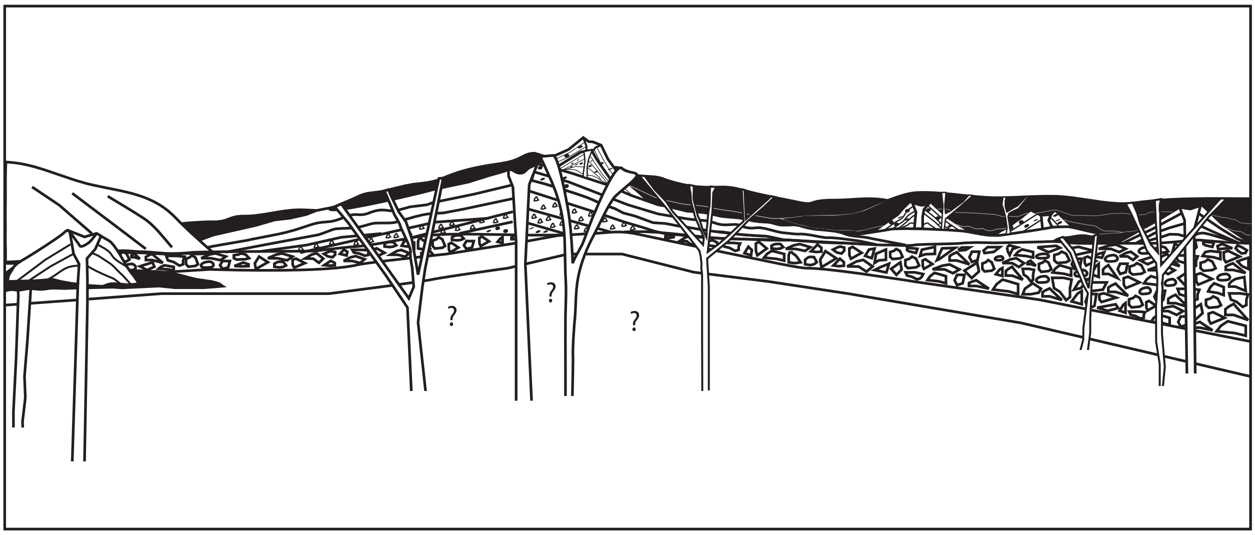

Fig 7.8 Stage 8: Mafic activity migrated outwards. A ceasation in volcanism occured and was succeeded by the intrusion of a multitude of predominantly trachyte dykes into the earlier formed deposits

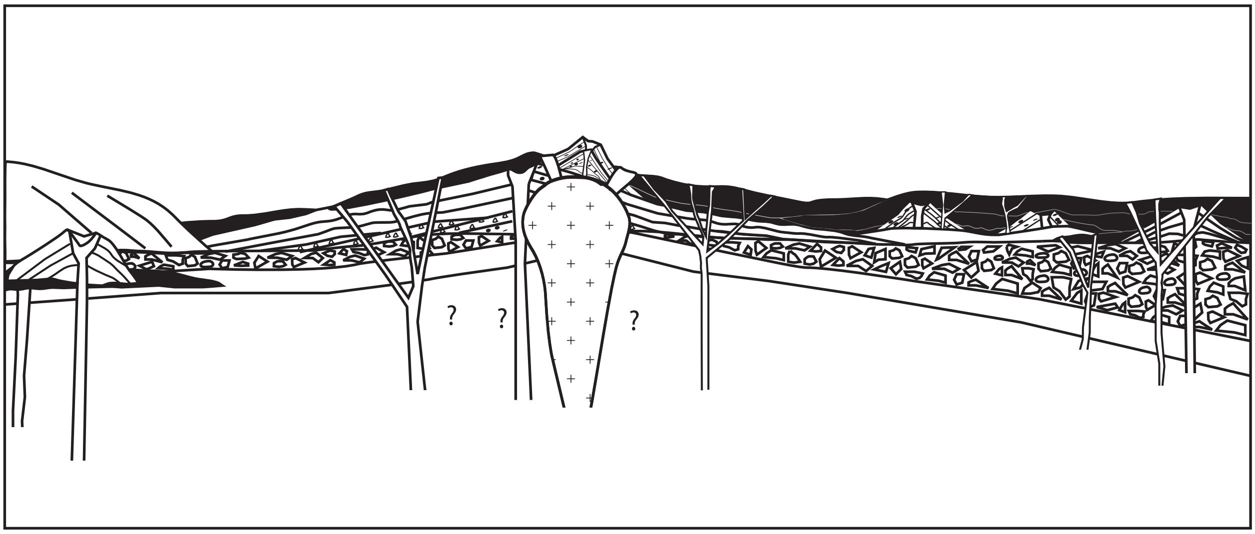

Fig 7.9 Stage 9: A remnant magma chamber started to ascend and subsequently intruded into the deposits of Akaroa Volcano at Onawe Peninsula.